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Development of Criteria for Extension of Applicability of Low Emission High Efficiency Coal Burners

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16. ABSTRACT

The report gives results of the first year's effort on this contract. Experimental studies were conducted at three scales to determine the influence of coal properties on NOx emissions. In addition, the use of sorbents to reduce SOx emissions from coal flames was investigated. Bench-scale (0.1 million Btu/hr) investigation concentrated on studies to define the effect of coal characteristics on fuel nitrogen conversion. Based on these investigations, the total coal nitrogen content does not appear to be the primary variable controlling fuel NO production in pulverized-coal flames. Experiments were conducted with research-design low-NOx burners at two scales (12.5 and 100 million Btu/hr) using three coal types. Under optimum conditions, the NOx emissions, typically below 200 ppm (dry at 0% O2), were only slightly dependent on coal characteristics. Preliminary investigations assessed the use of the low-NOx burner design to reduce NOx and SOx emissions by adding sorbents to the coal before the pulverizer. Limestone added this way gave 50, 70, and 80% reductions in SO2 emissions at calcium/sulfur molar ratios of 1, 2, and 3, respectively.

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Coal	Limestone	Stationary Sources	21D	08G
Burners	Calcium Carbonates		13A	
Combustion			21B	
Properties			14G	
Nitrogen Oxides			07B	
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DEVELOPMENT OF CRITERIA FOR EXTENSION OF APPLICABILITY OF LOW EMISSION, HIGH EFFICIENCY COAL BURNERS

FIRST ANNUAL REPORT

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ABSTRACT

The results of the first year's effort on EPA Contract 68-02-2667, "Development of Criteria for Extension of Applicability of Low-Emission, High-Efficiency Coal Burners," are presented. Experimental studies have been conducted at three scales to determine the influence of coal properties on NO_x emissions. In addition, the use of sorbents to reduce SO_x emissions from coal flames has been investigated.

Bench-scale (0.1×10^6 Btu/hr) investigation concentrated on studies to define the effect of coal characteristics on fuel nitrogen conversion. Based on these investigations, it appears that the total coal nitrogen content is not the primary variable controlling fuel NO production in pulverized-coal flames. Experiments were conducted with research-design low-NO_x burners at two scales (12.5 and 100×10^6 Btu/hr) using three coal types. Under optimum conditions, the NO_x emissions were typically below 200 ppm (dry at 0% O_2), and they were only slightly dependent on coal characteristics.

A prelimary series of investigations were carried out to assess the use of the low-NO_x burner design to reduce NO_x and SO_x emissions by adding sorbents to the coal before the pulverizer. Limestone added in this way gave 50, 70, and 80 percent reduction in SO_2 emissions at calcium/sulfur molar ratios of 1, 2, and 3, respectively.

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1.0 SUMMARY

Experimental studies have been conducted at three scales to determine the influence of coal properties on NO_x emissions over a wide range in operating conditions. In addition, the use of sorbents to reduce SO_x emissions from coal flames has been investigated.

Bench-scale ($0.1x10^6$ Btu per hour) investigations concentrated upon studies to define the effect of the physical and chemical characteristics of coals on fuel nitrogen conversion. The formation of thermal NO was prevented by the use of artificial oxidant mixtures ($Ar/CO_2/O_2$) free from molecular nitrogen. Results are presented showing the effect of fuel nitrogen content, initial fuel/air mixing processes, and particle size for both staged and unstaged conditions. Contrary to liquid fuels, where fuel NO emissions increase with total fuel nitrogen content, it appears that the total coal nitrogen content is not the primary variable controlling fuel NO production in pulverized coal flames. In addition, fuel NO_x formation appears to be relatively insensitive to thermal environment in a diffusion flame, whereas there is a strong dependence of fuel NO production on flame temperature in premixed pulverized coal flames. Lastly, the initial fuel/air contacting was found to have a major impact upon fuel NO production under both staged and unstaged conditions.

Experiments were also conducted using research design low NO_x burners at two scales (12.5 and 100x106 Btu/hr) using three coal types. Under optimum conditions the NO_x emissions were typically below 200 ppm (dry at 0 percent O_2). The results also suggest that the burner design is only mildly dependent on coal characteristics.

A preliminary series of investigations were carried out to assess the use of the low NO_x burner to control both NO_x and SO_x by adding dry sorbents to the coal before the pulverizer. Limestone mixed with the coal in calcium-to-sulfur molar ratios of 1, 2 and 3 gave 50, 70 and 85 percent reduction in SO_2 emissions respectively for low sulfur coal. At low calcium/sulfur ratios SO_2 reduction appeared to be enhanced by low NO_x operation. The results suggest that the low NO_x burner provides ideal conditions to maximize sorbent efficiency.

2.0 INTRODUCTION

The results of the first year's effort on EPA Contract 68-02-2667, "Development of Criteria for Extension of Applicability of Low Emission High Efficiency Coal Burners," are presented in this First Annual Report. This three-year program concerns the extension of the low emission coal burner technology developed under EPA Contract 68-02-1488. The overall program goal is being accomplished by meeting the following objectives:

- Expand the fuel capability of the burner to include the major types of solid fossil fuels projected for use by the utility industry.
- Explore additional burner concepts and configurations that show potential for improving the emission and thermal performance of pulverized coal burners.
- Determine the effects of multiple burner configurations that are encountered in utility boilers.
- Provide for direct comparison between the experimental burners being developed herein and the current state-of-the-art for commercially available coal burners.
- Arrange for coordination of the technology development program with boiler manufacturers and users.
- Provide testing in support of planned application of the burner technology.

The program designed to accomplish these goals is divided into the following seven tasks:

- Task 1 — Program Definition
- Task 2 — Screening Studies
- Task 3 — Single Burner Experiments
- Task 4 — Multiburner Experiments
- Task 5 — Current Baseline Evaluation
- Task 6 — Industry Coordination
- Task 7 — Data Analysis

The overall program task logic is presented in Figure 2-1. Task 1 is concerned with program definition and involves the preparation of three definitive plans: an overall experimental plan to define the scope of data to be obtained from the various experimental efforts; a fuels selection report to review the multitude of coals available and recommend which coals should be tested during the experimental efforts; and a report defining the detailed measurements and procedures which are necessary to the fundamental understanding and design of low emission coal burners.

Task 2 involves the execution of the Task 1 experimental plan at the smallest scale (100,000 Btu/hr) for fuel screening, concept definition and technique development. The end results lead to advanced concepts of low emission coal burners. Most of the detailed experimental measurement techniques that permit the fundamental understanding of the burning and emission phenomena are initiated in Task 2 since the small scale system provides for rapid and economical development. The concepts and techniques developed in Task 2 are then applied to Task 3 which involve the single burner testing at scales ranging from 10 to 120 M Btu/hr capacity. The starting point for Task 3 is based on the burner technology developed under Contract 68-02-1488. Since most large-scale applications using pulverized coal employ multiple burners, Task 4 involves extensions of Task 3 data to include testing of multiple burner arrays under varying operational conditions as well as with selected fuels from Tasks 2 and 3.

Task 5 involves testing of current commercial burners at the largest scales. The goals of this task are twofold. The first is to evaluate in the experimental facility the performance of burners used in the field so that correlations can be applied that will permit extrapolation of the results in the experimental combustors for field applications. The second is to generate direct comparison baseline data for current commercial burners. Task 7 provides the analysis effort for the entire program with the objectives of developing design criteria for practical systems.

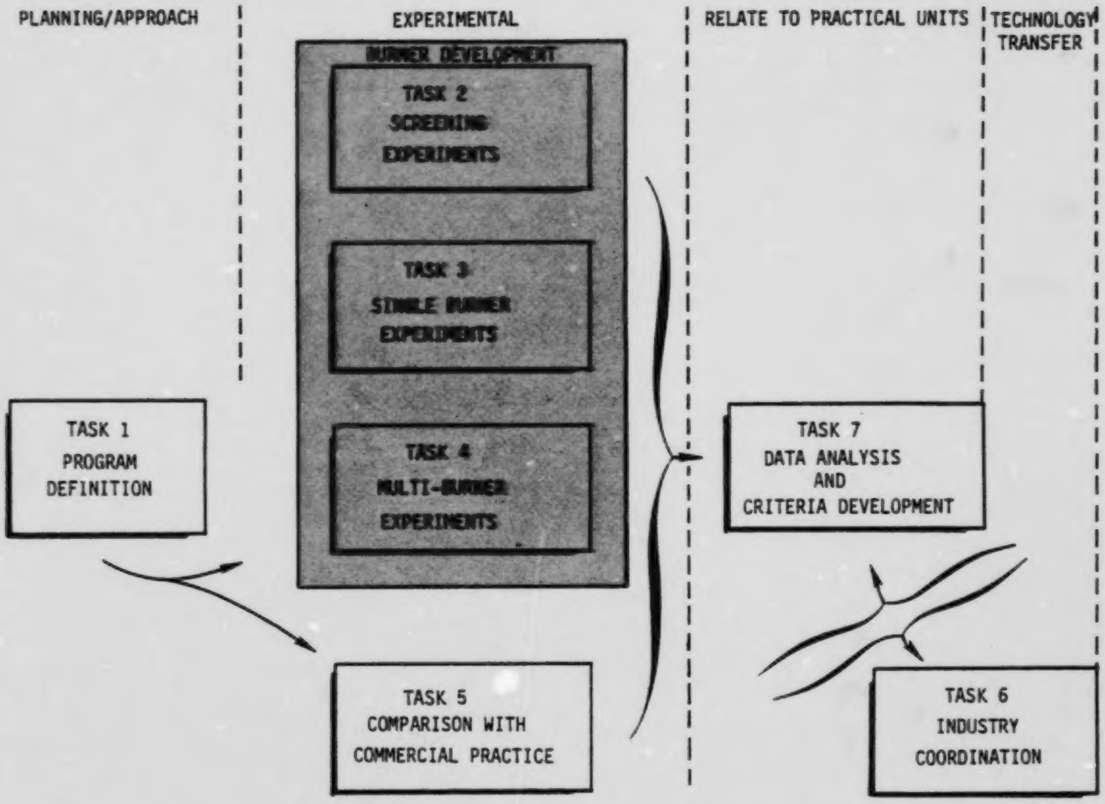

PLANNING/APPROACH
EXPERIMENTAL
RELATE TO PRACTICAL UNITS
TECHNOLOGY TRANSFER
BURNER DEVELOPMENT
TASK 2 SCREENING EXPERIMENTS
TASK 3 SINGLE BURNER EXPERIMENTS
TASK 4 MULTI-BURNER EXPERIMENTS
TASK 1 PROGRAM DEFINITION
TASK 5 COMPARISON WITH COMMERCIAL PRACTICE
TASK 7 DATA ANALYSIS AND CRITERIA DEVELOPMENT
TASK 6 INDUSTRY COORDINATION

Figure 2-1. Overall Program Logic.

To ensure effective and timely technology transfer, two panels exist under Task 6: (1) a technical panel, and (2) a technology transfer panel. The technical panel is composed of manufacturers, fuels suppliers, and research contractors which provide a critical review of the results and recommendations for future direction. In this way the results should be more useful to manufacturers who will be applying the technology in the future. The second panel is composed of government and association representatives who are also involved in burner development efforts. The purpose of this panel is to provide effective technology transfer between all major program efforts and ensure a minimum of duplication.

3.0 EXPERIMENTAL COMBUSTION FACILITIES AND DATA ACQUISITION SYSTEMS

The majority of the effort in this program involves experimental investigations which are being accomplished at four scales in three different combustors. The experimental systems and data measurement systems are discussed in this section.

3.1 Experimental Facilities

3.1.1 Small-Scale Facility (100,000 Btu/hr)

F3-1

The small-scale facility shown in Figure 3-1 has a design heat input rate ranging from 50 x 10^3 Btu/hr to 150 x 10^3 Btu/hr. This is equivalent to approximately 4 to 12 lbs/hr of bituminous coals.

Some of the versatile features of this facility are:

- Fuel Size Control — A combination of a pulverizer and a classifier enables the production of solid fuels with the desired size distribution.
- Oxidizer System — An artificially blended mixture consisting of three gases which can be used as the oxidizer reactant in place of air.
- Combustion Chamber Access — Ports are built into the furnace to facilitate visual and physical access. Visual observation is an important element of flame characterization. Physical access is necessary for oxidizer and additive injection, and sample extraction.

The small-scale system is made up of the following subsystems:

- Fuel Preparation
- Fuel Feed and Metering
- Oxidant
- Burner
- Combustor
- Sample Extraction and Treatment

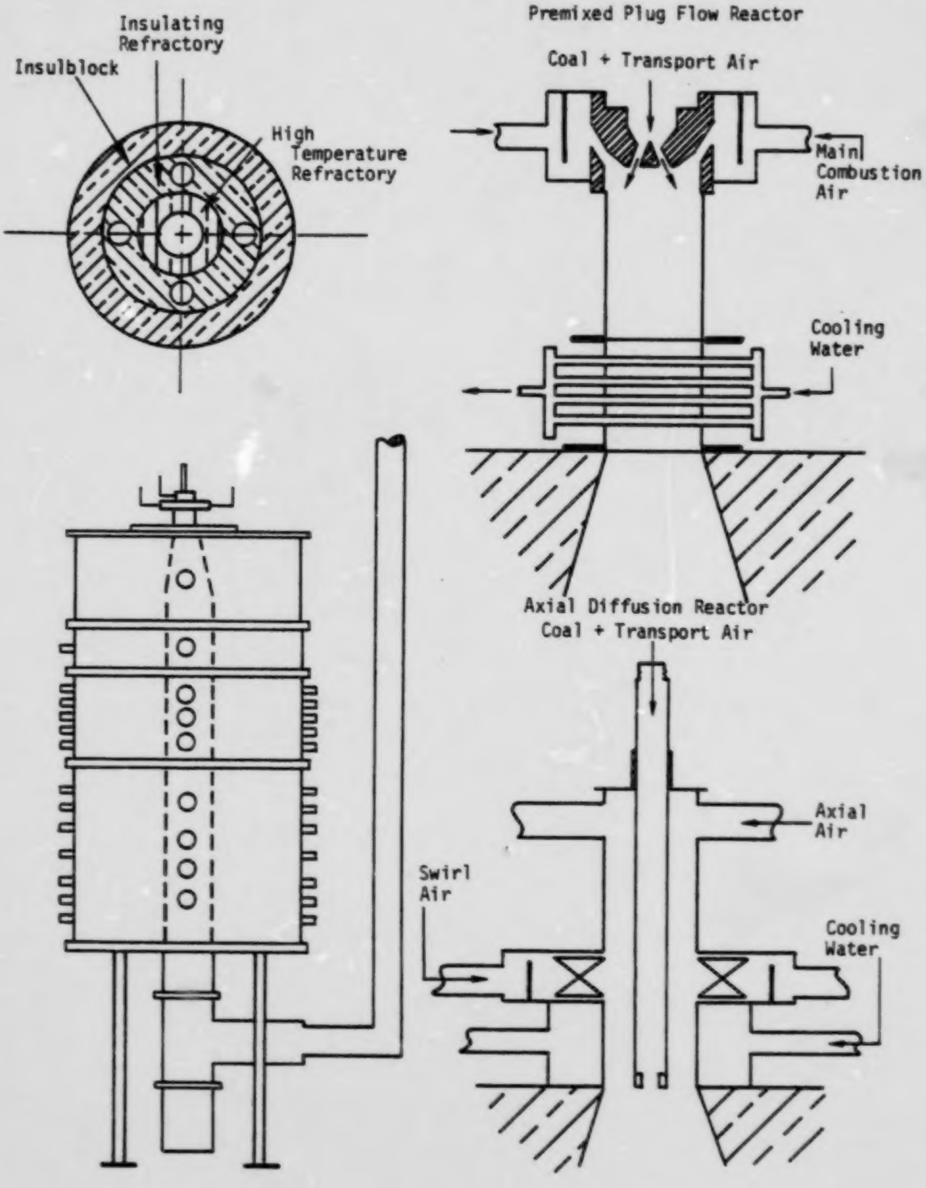

Insulating
Refractory
Insulblock
High
Temperature
Refractory
Premixed Plug Flow Reactor
Coal + Transport Air
Main
Combustion
Air
Cooling
Water
Axial Diffusion Reactor
Coal + Transport Air
Axial
Air
Swirl
Air
Cooling
Water

Figure 3-1. Details of Pulverized Coal Furnace System and Burners.

- Sample Analyses
- Safety and Electronics

The furnace is a refractory-lined, down-fired, single burner hot wall tunnel which consists of five disassemblable sections. Each section is made up of an outer steel shell and three layers of refractory insulation. The main combustion chamber is six inches in diameter. The furnace entry (top section) consists of a 12-inch long refractory quarl that diverges gradually from two inches to the full six-inch diameter. The half angle of the quarl is 10^{0}. The long quarl helps to eliminate recirculation. At seven axial positions two opposing 2-inch diameter access ports allow for probes or air injection. Rotated by 90^{0} at 13 axial positions, two 1-inch access ports are provided in the cast to allow for further sampling or air/additive injection. Four auxiliary firing chambers, 3 inches in diameter, are cast in the perimeter of the main combustion chamber with a center-to-center distance of 7.5 inches. With propane firing in these chambers the temperature in the main chamber can be raised to simulate adiabatic reactors.

Two reactors are available which have differing combustion characteristics:

1. Completely premixed fuel/air flame in a plug flow reactor.
2. Diffusion controlled flames as produced in an axial fuel jet surrounded by an annulus of combustion air.

These two configurations in conjunction with delayed fuel/air contact provide for a wide range in pertinent parameters for investigation of fuel/air contacting effects.

Premixed Plug Flow Reactor — The premixed plug flow reactor is also illustrated in Figure 3-1. In this design the transport air and the pulverized coal are injected radially outward at a 30^{0} angle with the vertical into a chamber in six 1/8-inch round jets. The main combustion air is injected radially inward into the chamber in six round jets opposing the coal jets. Mixing between the air and the coal is achieved by dynamic mixing due to jet impingement and turbulence within the mixing chamber.

This burner produces predominately one-directional flow, and backmixing is negligible. In order to prevent ignition in the mixing chamber caused by radiation from the hot furnace, three banks of 1/8-inch water-cooled tubing are arranged so that there is no straight line of sight between the furnace and the mixing chamber.

Axial Diffusion Reactor — The lower schematic shown in Figure 3-1 illustrates the design features of the controlled mixing burner. To obtain an axial diffusion flame, a 3/4-inch O.D. coal injector with a 0.44-inch diameter round hole at the tip is used. The size of the hole in the injector is determined so as to give a velocity of 30 ft/sec at 70 x 10^3 Btu/hr with 15 percent of the theoretical air as transport air. The nominal velocity of the combustion air is selected by installing flow restricting collars of various sizes. When only axial momentum is imparted on the combustion air, the bluff body effect of the coal injector tube induces recirculation of hot gases to heat and ignite the coal. Ignition of most bituminous coals takes place at about 4 inches from the point of injection. For high moisture coals, ignition is displaced further downstream. Regardless of the point of ignition, a central core of fuel is maintained. As tangential momentum is gradually introduced to the combustion air, the flame undergoes a transition from a detached flame to an attached flame. With sufficiently high tangential momentum, hot combustion gases flow recirculating back alone the axis to ignite the incoming coal.

In the transition region, recirculation is not sufficiently intense to initiate ignition at the fuel injector. Consequently, the fuel is intensely mixed with the swirling air and is thrown to the hot furnace walls where ignition starts at protrusions on the surface.

Coals in lump sizes from one to five inches are stored in covered 55-gallon drums. Prior to being fired in the furnace, the coals are prepared by the following steps:

1. Crushing of oversized coal — This is a manual operation. This step provides 1/4-inch pellets that are fed into the pulverizer.

2. Pulverization — A Bantam micro-pulverizer is used for this operation. By selecting discharge screens having openings with a specific size, the product size distribution can be altered.

Coal feed is controlled by an Acrison Model 105 Volumetric Feeder with a variable speed controller. At low screw rpm,solids are delivered in a pulsating manner.

The coal is pneumatically transported to the burner via a 3/8-inch I.D. tube. Typically, the coal/air mixture has a solids loading of 0.055 lbs solid/SCF air (0.76 lb solid/lb air). Velocity of the coal/air mixture is approximately 20 ft/sec. A calibrated feeder is used to meter coal to the reactor.

Oxidizer System — The oxidant system is shown in Figure 3-2. During ordinary operation, combustion air at 100 psig is supplied by a compressor. The air is filtered with two aerosol cartridge filters to remove any foreign matter such as oil, water and corrosion products. The air is then regulated down to 45 psig separately at the rotameters. Needle valves downstreams of the rotameters are used to control the flow rates. With this arrangement, all rotameters can be operated at a constant pressure (usually 45 psig) which minimizes the error due to pressure correction.

3.2

When an **artificial** oxidizer is used, the component gases are supplied in Union Carbide high pressure cylinders. A parallel system of rotameters, regulators and valves allow three gas components to be blended to provide the desired mixture.

As described earlier, the oxidizer can be distributed into five streams, providing for coal transport, burner and staged air. Each stream is monitored with a rotameter and controlled with a regulator-needle valve combination. For flows requiring high accuracy, Brooks 600 mm long high accuracy rotameters (±1 percent full-scale instantaneous) are used. For flows that do not require this high precision, Dwyer RMC-series rotameters (±2 percent full-scale) are used.

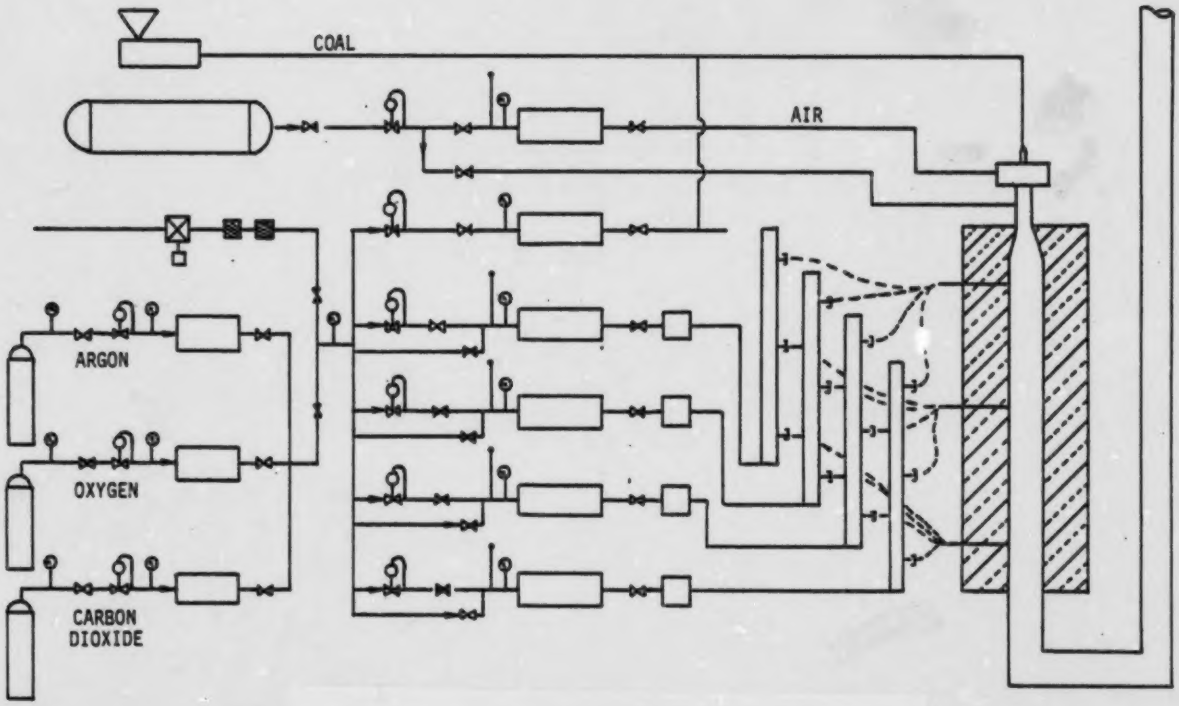

COAL
AIR
ARGON
OXYGEN
CARBON DIOXIDE

Figure 3-2. Small-Scale Reactor Oxidant System.

The air streams can be heated by electrical heaters to temperatures up to 900°F, and utilize tubular heater elements manufactured by Chromalox. For each heater an Alnor Pyromatric II controller and a Chromalox high limit controller are used to control exit air and heater element temperatures respectively.

The heated air streams are fed to four independent manifolds which are mounted alongside the combustor. With this system, air can be injected at various axial locations within the combustor. Staged air is injected into the combustor tunnel via two opposing 3/8-inch stainless steel tubes. With 60 percent of theoretical combustion air injected through these tubes, the jets have a velocity on the order of 200 ft/sec.

3.1.2 Pilot-Scale Facilities

Large Watertube Simulator (50 to 120 MBtu/hr)

Full-scale simulation of the geometry and thermal environment of a utility watertube boiler is provided by the Large Watertube Simulator (LWS). The LWS facility layout with support systems is illustrated in Figure 3-3. The LWS has been used at firing rates ranging from 50 to 100 x 10^6 Btu/hr and has multi-fuel capability. The combustor is 54 feet tall, 28 feet deep and 16 feet wide. The LWS incorporates a movable back wall to provide for a fourfold variation of the furnace volume as indicated in Figure 3-4, and a range of firebox residence times can be obtained that are comparable with field utility boilers. The construction and variable geometry also provide the flexibility needed for investigating multiple burner arrays.

The outer shell and the movable back wall of the combustor are fabricated from large sections of preformed, corrugated mild steel sheet. The structure is stabilized by welded purlins which are also formed from steel sheet. The shell is completely unrestrained in regard to thermal growth in the vertical direction, and the corrugations provide for growth in the horizontal direction. The walls of the combustion chamber are cooled by water sprays supplied from manifolds incorporated into the main structural

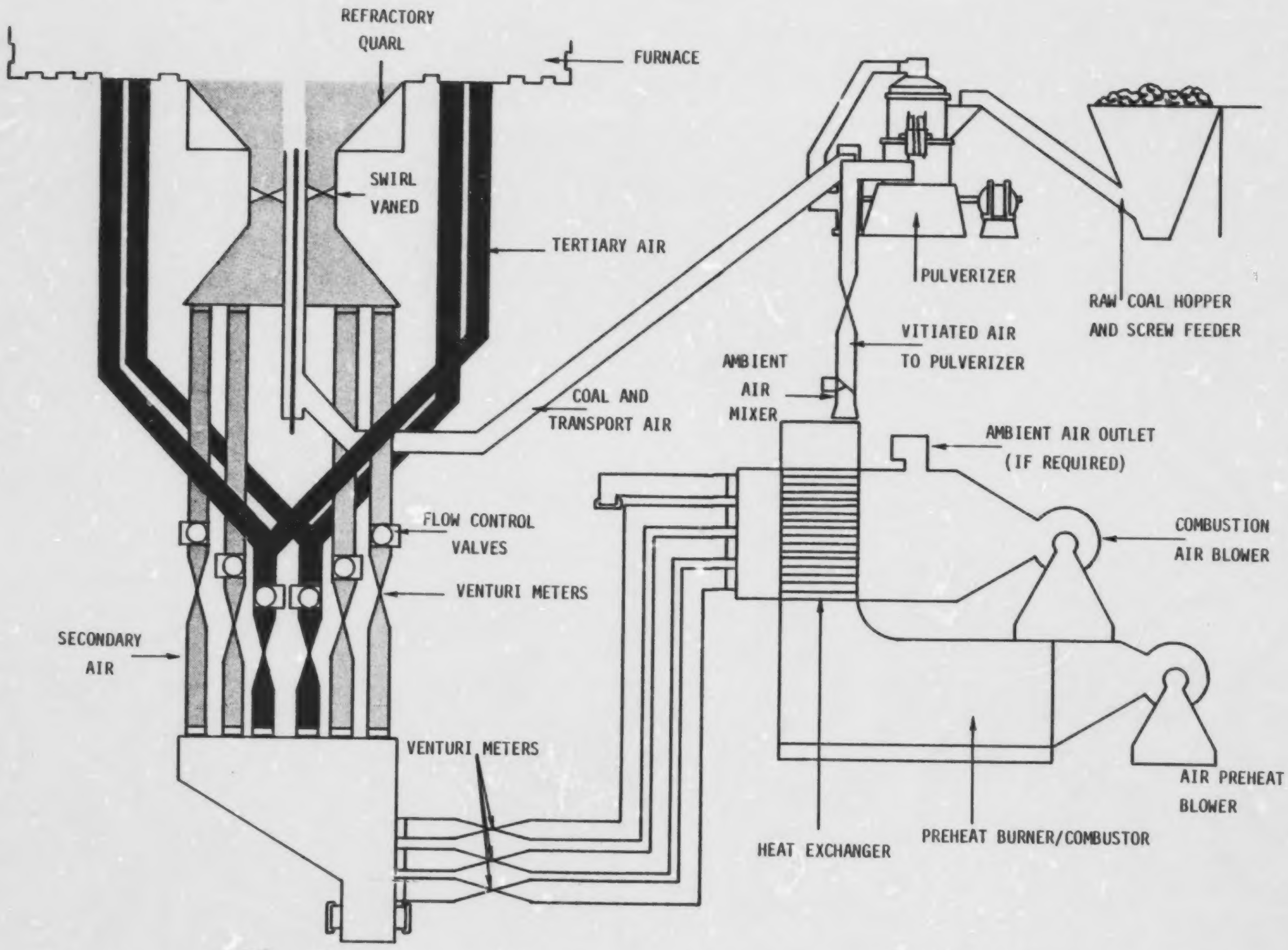

REFRACTORY QUARL
FURNACE
SWIRL VANED
TERTIARY AIR
PULVERIZER
RAW COAL HOPPER AND SCREW FEEDER
VITIATED AIR TO PULVERIZER
AMBIENT AIR MIXER
COAL AND TRANSPORT AIR
AMBIENT AIR OUTLET (IF REQUIRED)
FLOW CONTROL VALVES
COMBUSTION AIR BLOWER
VENTURI METERS
SECONDARY AIR
VENTURI METERS
AIR PREHEAT BLOWER
PREHEAT BURNER/COMBUSTOR
HEAT EXCHANGER

Figure 3-3. Large Watertube Simulator (LWS) Test Facility.

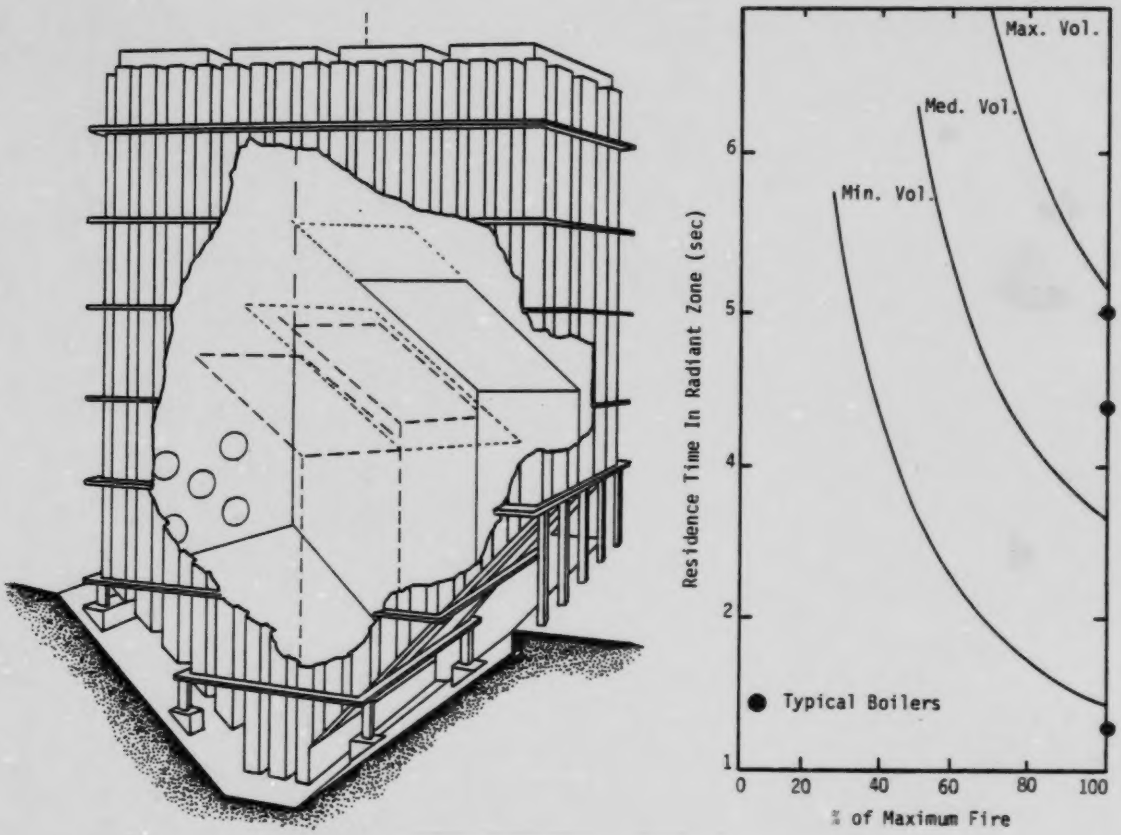


Figure 3-4. Variable Geometry LWS Combustor.

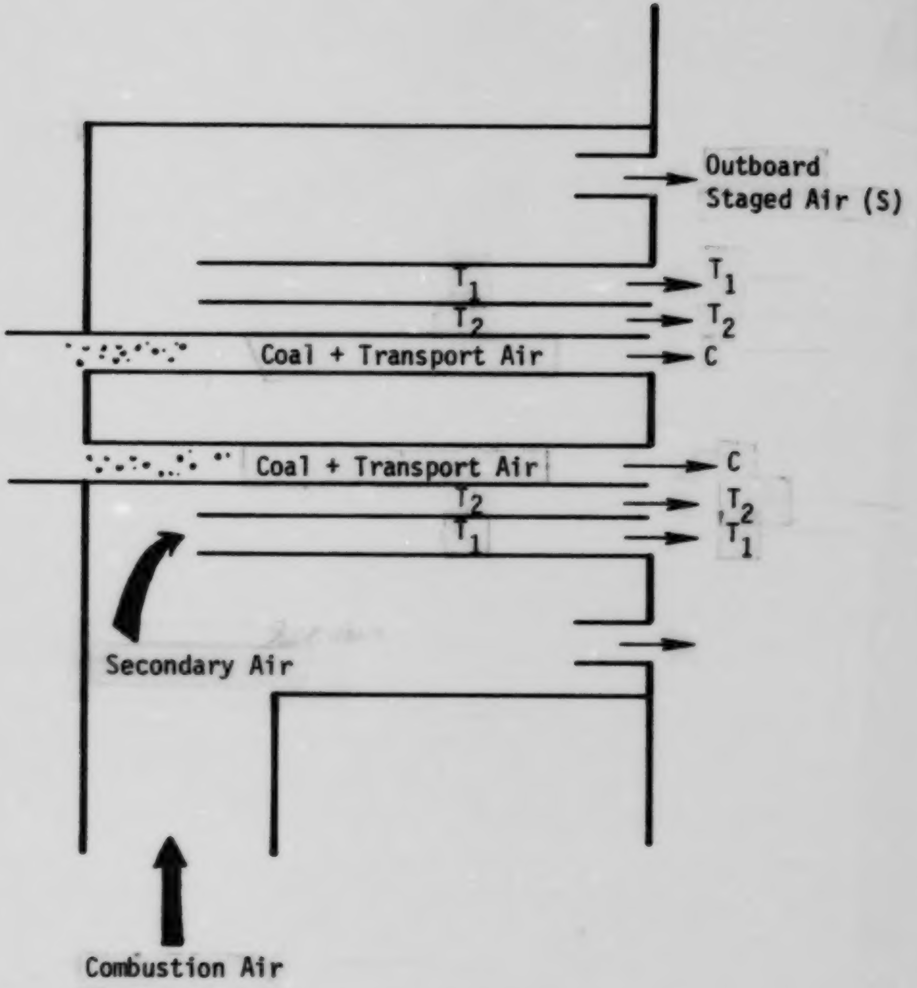
frame, spraying on the outside of the modular combustion chamber walls. Each spray head is controlled by an attached two-stage solenoid valve which is operated in a pulsed duration modulation mode. The spray controls are divided to operate sprays in several zones, thus allowing flexibility of wall temperature distribution control.

Airflow to the combustor is supplied by a blower driven with an internal combustion engine. Because the experimental coal burners require multiple locations for air injection, a manifolding system is provided which allows the combustion airflow to be controlled and monitored in many individual streams.

A schematic representation of the separate burner air streams which can be monitored is presented in Figure 3-5. The total airflow is made up of:

- Primary air which is that required to transport the coal from the pulverizer to the burner;
- Secondary air which is supplied through an annular throat surrounding the coal injector. This stream can be split into an inner and outer flow to allow for controlled mixing in the early part of the flame; and
- Outboard staged air which provides the burnout air and oxidizing envelope for the low emission flame.

The airflow in the various streams is monitored during the test program by individual venturis. For multiple or commercial burners the airflow is monitored by calibrating the airflow as a function of pressure within the windbox. During the system checkout, pitot probe traverses were made in the various ducts on several dimetral planes, both as a check against the airflow calibration and to ensure uniform flow within each duct. Preheated combustion air is supplied from a separately fired preheater. The combustion air supply can be preheated to a maximum temperature of 800°F independently from the firing rate of the combustor. Solids are processed by a commercial Raymond CE pulverizer which has a capacity of about six tons/hr. The fuel is transported pneumatically from the pulverizer to the combustor.


Outboard Staged Air (S)
T_1
T_2
Coal + Transport Air
C
Coal + Transport Air
C
T_2
T_1
Secondary Air
Combustion Air

Total Airflow = Primary Air + Secondary Air + Outboard Staged Air

$$\underset{C}{\text{Primary Air}} + \underset{(T_1 + T_2)}{\text{Secondary Air}} + \underset{S}{\text{Outboard Staged Air}}$$

Figure 3-5. Airflow Distribution.

Small Watertube Simulator Facility

The tests at 12 MBtu/hr heat input with the low NO_x burner are carried out in the thermal environment typical of water wall boilers in a small watertube simulator (SWS). The geometry of the simulator is trapezoidal which is similar to the most populat design of watertube boilers. The unit is schematically illustrated in Figure 3-6, along with a layout of the support systems. The SWS can be fired at rates ranging from 4 to 16 x 10^6 Btu/hr. Other features of the SWS include:

F 3-6

- a ceramic front wall which can be moved to vary the furnace depth up to its maximum of 11 feet;
- sheet steel side and back walls which can be cooled by a pulse water spray system;
- a stack heat exchanger that uses the high temperature combustion products to preheat the incoming combustion air up to 600°F; and
- multi-fuel capability.

The coal is pulverized by a high-speed hammer mill and pneumatically transported cold to the burner. The fineness of the coal is controlled by screens. After pulverization the fuel is pneumatically conveyed directly from the pulverizer to the combustor at a rate of up to 1000 lb/hr or 200 SCFM. Individual control and measurement is provided for each of the numerous air and fuel streams necessary to the staged burner concept. The airflow to various burner input streams is controlled in the same manner as described for the LWS.

Data Acquisition System

Data acquisition/reduction and control of burner/furnace operations are accomplished from the control panel illustrated in Figure 3-7. The output from the various sensors and analyzers is sent to a data logger in series with an HP Model 9825A desk computer. A multipen recorder is used as a continuous signal monitor and recorder of the gas analyzers'

F 3-7

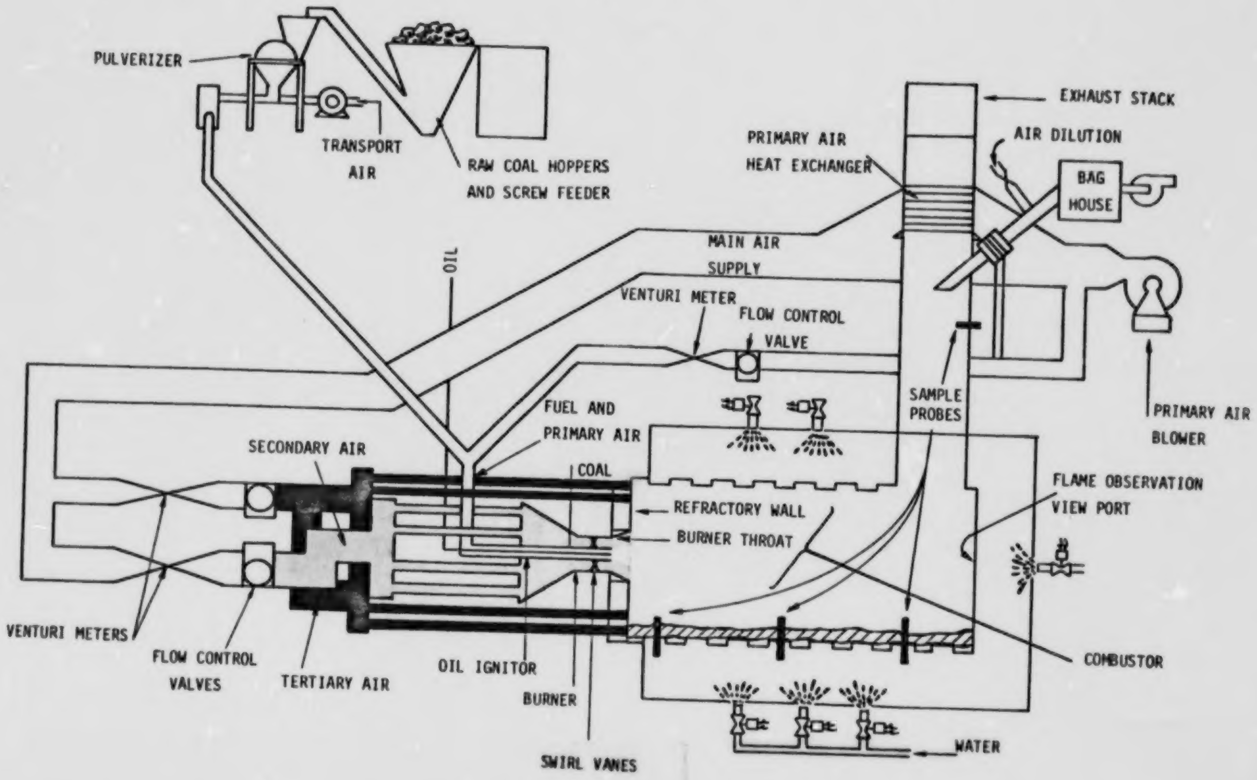

PULVERIZER
TRANSPORT AIR
RAW COAL HOPPERS AND SCREW FEEDER
EXHAUST STACK
AIR DILUTION
PRIMARY AIR HEAT EXCHANGER
BAG HOUSE
MAIN AIR SUPPLY
OIL
VENTURI METER
FLOW CONTROL VALVE
SAMPLE PROBES
PRIMARY AIR BLOWER
FUEL AND PRIMARY AIR
SECONDARY AIR
COAL
REFRACTORY WALL
BURNER THROAT
FLAME OBSERVATION VIEW PORT
VENTURI METERS
FLOW CONTROL VALVES
TERTIARY AIR
OIL IGNITOR
BURNER
SWIRL VANES
COMBUSTOR
WATER

Figure 3-6. Small Watertube Simulator (SWS) Test Facility.

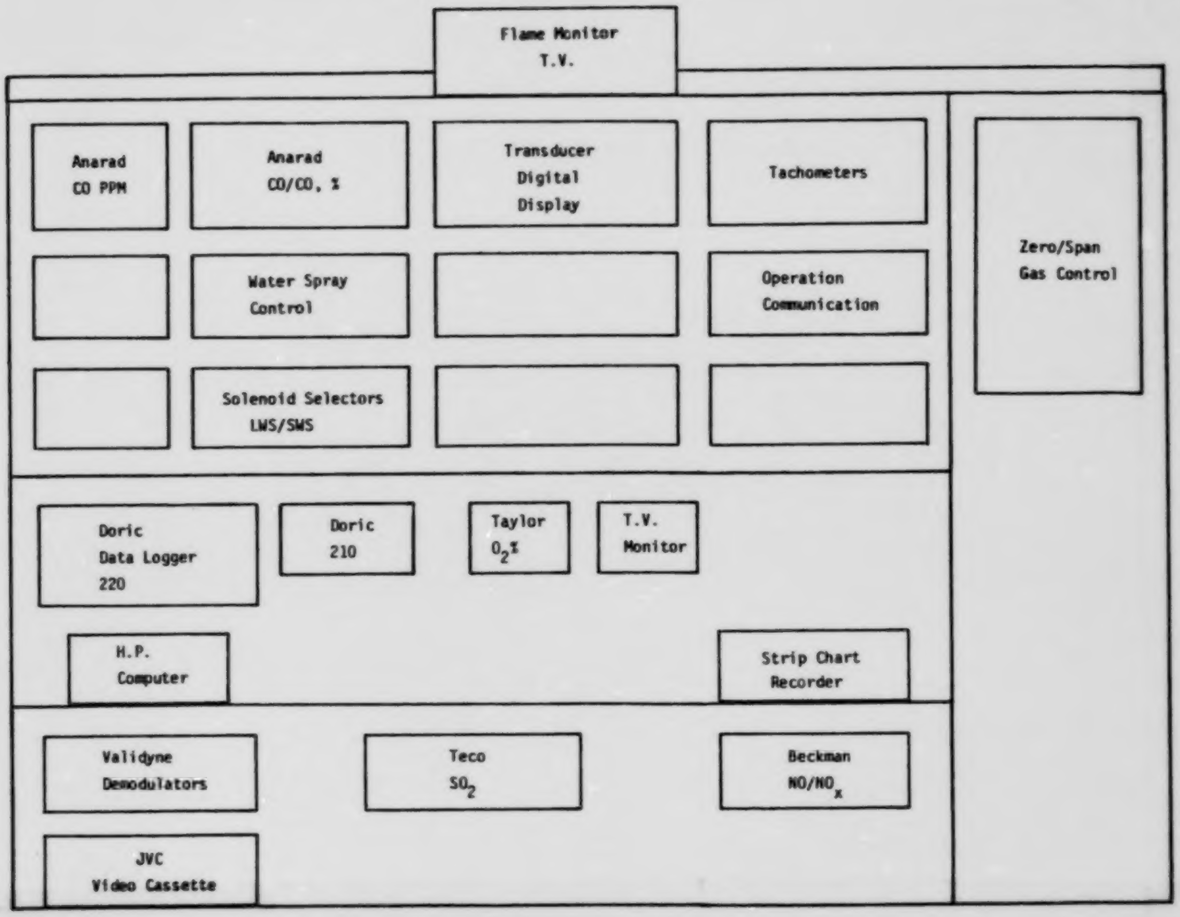
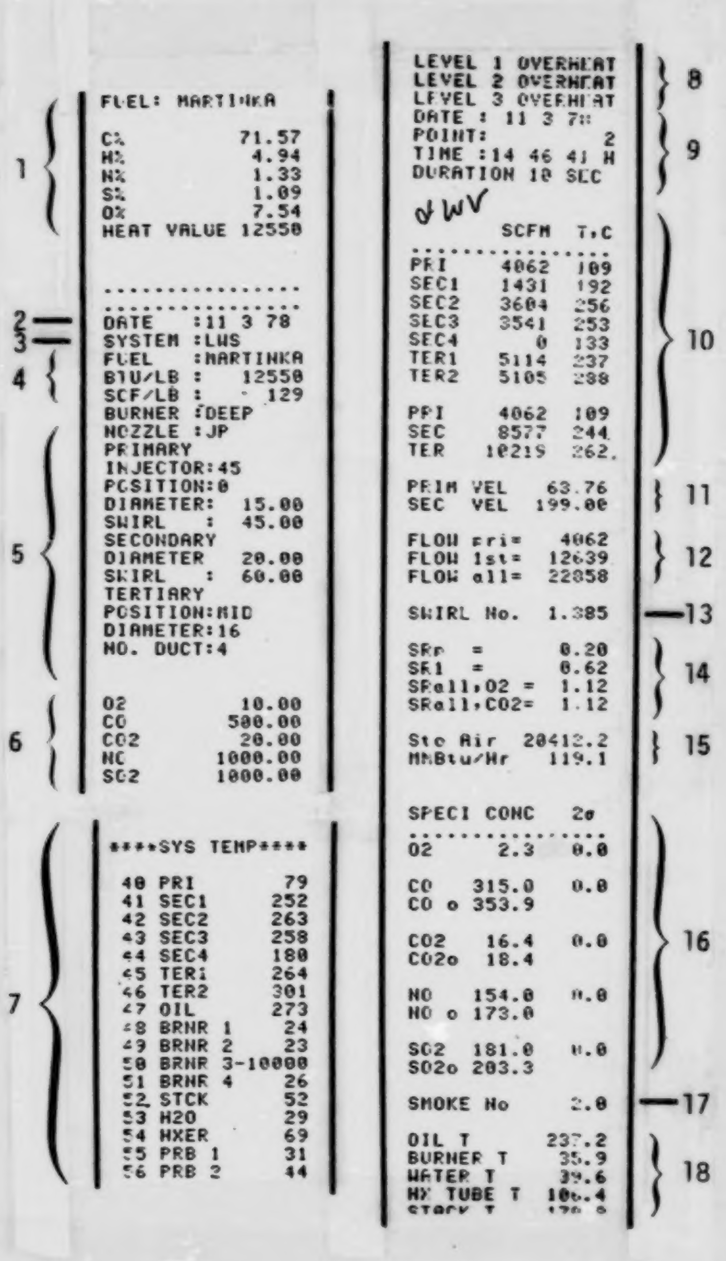

Flame Monitor
T.V.
Anarad
CO PPM
Anarad
CO/CO$_2$ %
Transducer
Digital
Display
Tachometers
Zero/Span
Gas Control
Water Spray
Control
Operation
Communication
Solenoid Selectors
LWS/SWS
Doric
Data Logger
220
Doric
210
Taylor
O$_2$%
T.V.
Monitor
H.P.
Computer
Strip Chart
Recorder
Validyne
Demodulators
Teco
SO$_2$
Beckman
NO/NO$_x$
JVC
Video Cassette

Figure 3-7. Control and Data Acquisition Layout.

output. Typical output from the desk computer is shown in Figure 3-8. The contents of the output, as numerically labeled in Figure 3-8, are described below:

1. Input of fuel properties - required if not a routine fuel
2. Date
3. Combustor name for program code selection
4. Fuel combustion values
5. Burner systems description and dimensions
6. Range settings of analyzers
7. Complete temperature scan - optional
8. Warning messages
9. Date, data point number, time and duration of sample scan - output
10. Individual and zone airflows - calculated from venturi calibration tables and measured temperatures
11. Calculated velocities using burner flows and dimensions
12. Total airflow (to each zone)
13. Swirl number calculated from burner settings, dimensions and flows
14. Calculated stoichiometric ratios in the primary, primary-plus -secondary, and overall furnace based on oxygen and on carbon dioxide
15. Calculated stoichiometric airflow for the attendant firing rate
16. Sample gas (dried) composition as measured by the analyzers and the composition reduced to zero percent excess oxygen (subscript 0)
17. Visual determination of smoke number - input
18. Temperatures desired for continous output


1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18

```
FUEL: MARTINKA

C%           71.57
H%            4.94
N%            1.33
S%            1.09
O%            7.54
HEAT VALUE 12550


.................
.................
DATE    :11 3 78
SYSTEM  :LWS
FUEL    :MARTINKA
BTU/LB  :    12550
SCF/LB  :      129
BURNER  :DEEP
NOZZLE  :JP
PRIMARY
INJECTOR:45
POSITION:0
DIAMETER:  15.00
SWIRL    :  45.00
SECONDARY
DIAMETER    20.00
SWIRL    :  60.00
TERTIARY
POSITION:MID
DIAMETER:16
NO. DUCT:4

O2           10.00
CO          500.00
CO2          20.00
NO         1000.00
SO2        1000.00
```

```
****SYS TEMP****

 40 PRI          79
 41 SEC1        252
 42 SEC2        263
 43 SEC3        258
 44 SEC4        180
 45 TER1        264
 46 TER2        301
 47 OIL         273
 48 BRNR 1       24
 49 BRNR 2       23
 50 BRNR 3-10000
 51 BRNR 4       26
 52 STCK         52
 53 H2O          29
 54 HXER         69
 55 PRB 1        31
 56 PRB 2        44
```

```
LEVEL 1 OVERHEAT
LEVEL 2 OVERHEAT
LEVEL 3 OVERHEAT
DATE : 11 3 78
POINT:           2
TIME :14 46 41 H
DURATION 10 SEC
✓WV
       SCFM   T,C
.................
PRI     4062   109
SEC1    1431   192
SEC2    3604   256
SEC3    3541   253
SEC4       0   133
TER1    5114   237
TER2    5105   288

PRI     4062   109
SEC     8577   244
TER    10219   262

PRIM VEL   63.76
SEC  VEL  199.00

FLOW pri=   4062
FLOW 1st=  12639
FLOW all=  22858

SWIRL No.  1.385

SRp  =      0.20
SR1  =      0.62
SRall,O2 =  1.12
SRall,CO2=  1.12

Sto Air  20412.2
MMBtu/Hr   119.1


SPECI CONC   2σ
.................
O2      2.3   0.0

CO    315.0   0.0
CO o  353.9

CO2    16.4   0.0
CO2o   18.4

NO    154.0   0.0
NO o  173.0

SO2   181.0   0.0
SO2o  203.3

SMOKE No      2.0

OIL T       237.2
BURNER T     35.9
WATER T      39.6
HX TUBE T   106.4
STACK T
```

Figure 3-8. Desk Computer Output.

Various options are available for data acquisition which include sample data averaging over a specified time interval, data elimination by variational limits, etc.

3.2 General Output Measurements

Examples of output measurements being routinely measured during the program are:

- Gaseous pollutant and performance measurements. NO_x, SO_2, CO, unburned hydrocarbons (UHC), CO_2, O_2.
- Solid particle measurements. Solids extracted both from the fly ash and the bottom ash for analysis of N_2, C, S and elemental composition.
- Flame characteristics such as flame shape, stability, in-flame and peripheral-flame performance, ignition and noise.

For each specific measurement a determination has been made of the required frequency of these measurements consistent with technical requirements and cost-effectiveness. For this study the frequency of the specific measurements is presented in Table 3-1. In general, the continous and/or intermittent measurements and recordings are made for all inputs, the usual gas species output and a comprehensive range of temperatures. This allows continuous definition of the overall low NO_x burner performance. In addition to the overall continuous measurements, intermittent measurements as indicated in Table 3-1 are being performed for detailed characterization to evaluate the overall performances necessary for burner applications and the effects of low NO_x operation on other potential pollutants. The overall layout of the instrumentation for the varoius facilities is illustrated in Figure 3-9 and are described below.

T3-1

F3-9

During the first year's effort only the exhaust gas species were measured. Solids sampling, as well as grab sampling for wet analysis, are planned during the second and third year of the program. Therefore, only the continuous exhaust gas measurements systems are discussed.

Table 3-1. General Measurement Scheme

	Routine		Non Routine			
Gas	CO, CO_2, O_2, NO	SO_2	UHC, NO_x SO_x, HCN, NH_3	Complex Organics XS	—	Bio Assay
Particulate	None		C, H, N, Ash	Sulfur Mass Size	Morphology Trace Elements, Large Organic Material	
Physical	Temperature		—	Velocity	—	
Variables	Many ——————→ Limited					

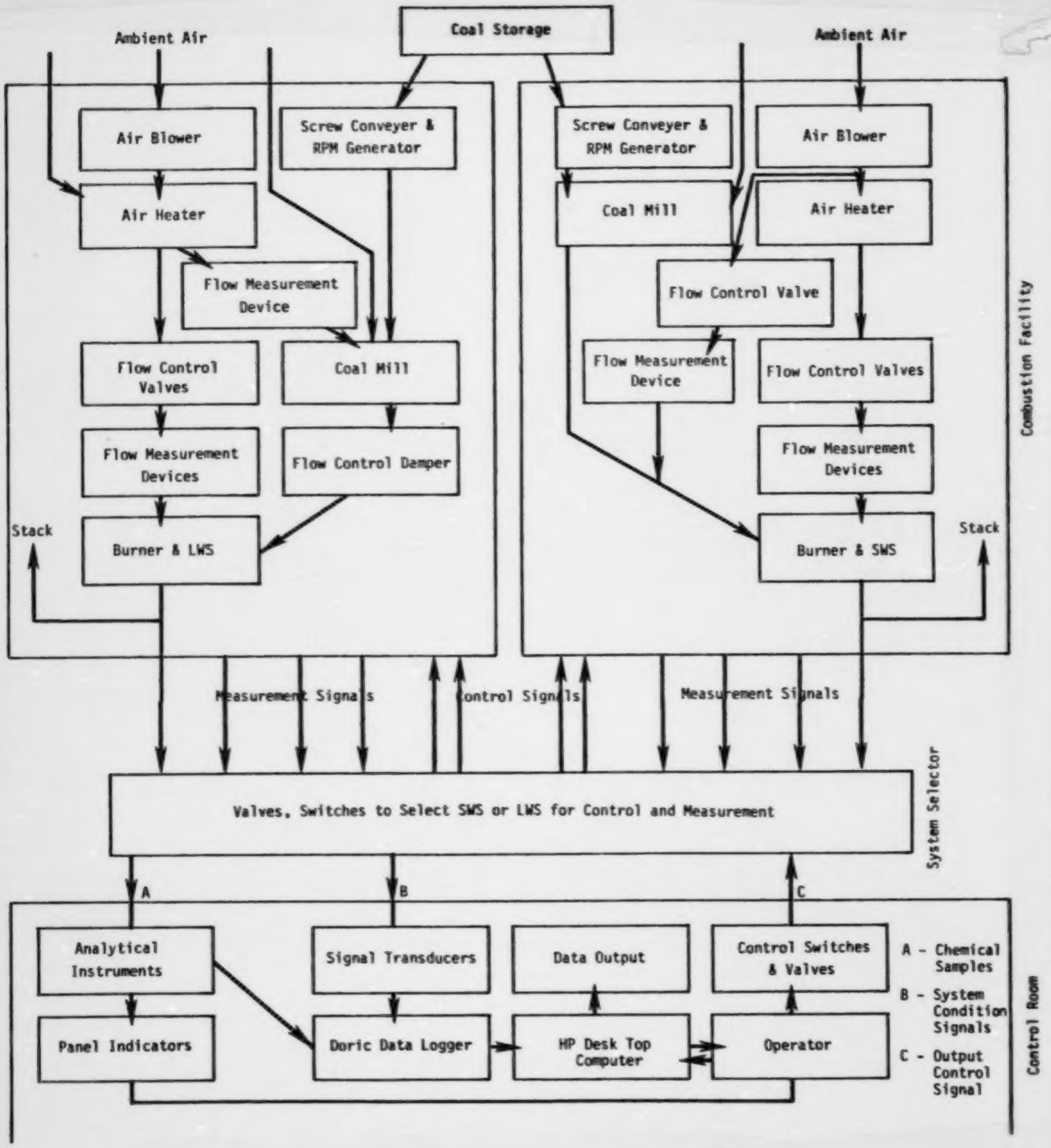

Coal Storage
Ambient Air
Ambient Air
Air Blower
Screw Conveyer & RPM Generator
Screw Conveyer & RPM Generator
Air Blower
Air Heater
Coal Mill
Air Heater
Flow Measurement Device
Flow Control Valve
Flow Control Valves
Coal Mill
Flow Measurement Device
Flow Control Valves
Flow Measurement Devices
Flow Control Damper
Flow Measurement Devices
Stack
Burner & LWS
Burner & SWS
Stack
Combustion Facility
Measurement Signals
Control Signals
Measurement Signals
Valves, Switches to Select SWS or LWS for Control and Measurement
System Selector
A
B
C
Analytical Instruments
Signal Transducers
Data Output
Control Switches & Valves
Panel Indicators
Doric Data Logger
HP Desk Top Computer
Operator
A - Chemical Samples
B - System Condition Signals
C - Output Control Signal
Control Room

Figure 3-9. Overall Scheme of Measurement and Control of SWS/LWS Facilities.

T3-2
F3-10
3-11

The exhaust gas composition is determined using the instrumentation listed in Table 3-2. The flow schematic for the exhaust gas analyzers is presented in Figure 3-10, and the sample conditioning system is shown in Figure 3-11. Instrument zero and span may be accomplished by directing calibration gases to the instruments or to the entry of the sample train. The former provides for direct calibration of each instrument, whereas the latter is essentially a calibration of the entire sample train. Sample conditioning consists of water and particulate removal. Two water refrigerator traps are used to provide water removal as soon as possible from the sample and after compression by the sample pump. A cyclone and/or filters of various collection efficiencies and materials are used for particulate removal. The final filter provides for 99.99 percent retention of 0.6 micron particles. Single orifice probes with a water cooling jacket are made of stainless steel. In the multiple probe array used in the LWS the probes are manifolded externally so that any individual probe can be monitored. Teflon lines are used for sample and calibration gas transfer.

Gas samples from the combustors are withdrawn from the sample probe(s) and flow vertically downwards through an ice bath. The bath consists of a five-foot vertical length of Teflon tubing surrounded by ice water. This tubing terminates with a tangential throw tube into a glass water trap of minimum volume and residence time. The gaseous output from the water trap is transferred in a Teflon tube to a dual head sample pump located atop the control house. After the pressurizing pump, the sample flows vertically downwards through a second ice bath which consists of a five-foot stainless steel tube surrounded by ice water. This S.S. Tubing terminates with a tangential throw tube into a S.S. water trap. The gaseous output from the second trap then flows through a filter to a sample manifold. Filters of various grades and materials, including spectro grade glass fiber (borosilicate glass fiber bonded with fluorocarbon resin) and Teflon, can be located anywhere along the sample train. Parallel samples from the sample manifold flow through regulation valves to the individual analyzers. Fine particulate filters are used upstream

Table 3-2. Analytical Instruments for Combustion Gases

Species	Analytical Method/Principle	Accuracy	Range (Volumetric Concentrations)
CO_2	Non-Dispersive Infrared Analysis - differential spectral energy absorbed by sample gas relative to carrier gas is proportional to specific concentration	± 3%	0 - 40%
CO	Same	± 3%	0 - 12% 0 - 1,000
O_2	Paramagnetic Analysis - paramagnetic characteristics of a sample gas containing oxygen is porportional to the oxygen concentration	± 3%	0 - 100% 0 - 25% 0 - 10%
NO/NO_x	Chemiluminescent Analysis - intensity of spectral emission from chemiluminescence of excited state NO_2 (converted 0 - 1% from NO) is proportional to NO in sample gas	± 3%	0 - 10,000 ppm 0 - 2,500 ppm 0 - 1,000 ppm 0 - 250 ppm 0 - 100 ppm 0 - 10 ppm
SO_2	Pulsed Fluorescence - intensity of spectral emission from the fluorescence of excited state SO_2 is proportional to the SO_2 concentration	± 3%	0 - 5,000 ppm 0 - 1,000 ppm 0 - 500 ppm 0 - 100 ppm 0 - 50 ppm
HC	Flame Ionization Detector - electrical conductivity properties of a hydrogen flame doped with sample gas is proportional to the number of carbon atoms in the sample	± 3%	0 - 10,000 ppm 0 - 5,000 ppm 0 - 1,000 ppm 0 - 100 ppm

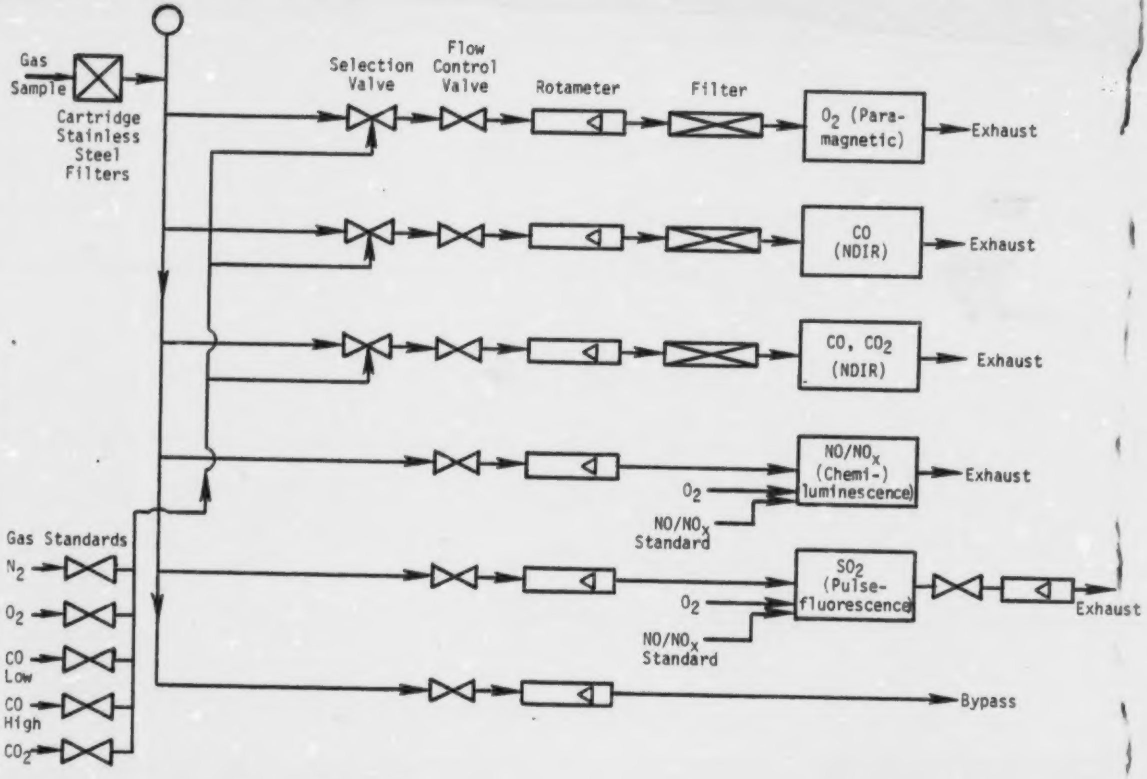

Gas Sample
Cartridge Stainless Steel Filters
Selection Valve
Flow Control Valve
Rotameter
Filter
O2 (Paramagnetic)
Exhaust
CO (NDIR)
Exhaust
CO, CO2 (NDIR)
Exhaust
NO/NOx (Chemi-) luminescence)
Exhaust
O2
NO/NOx Standard
Gas Standards
N2
O2
CO Low
CO High
CO2
SO2 (Pulse-fluorescence)
Exhaust
O2
NO/NOx Standard
Bypass

Figure 3-10. Flow Systems for Exhaust Gas Analyzers.

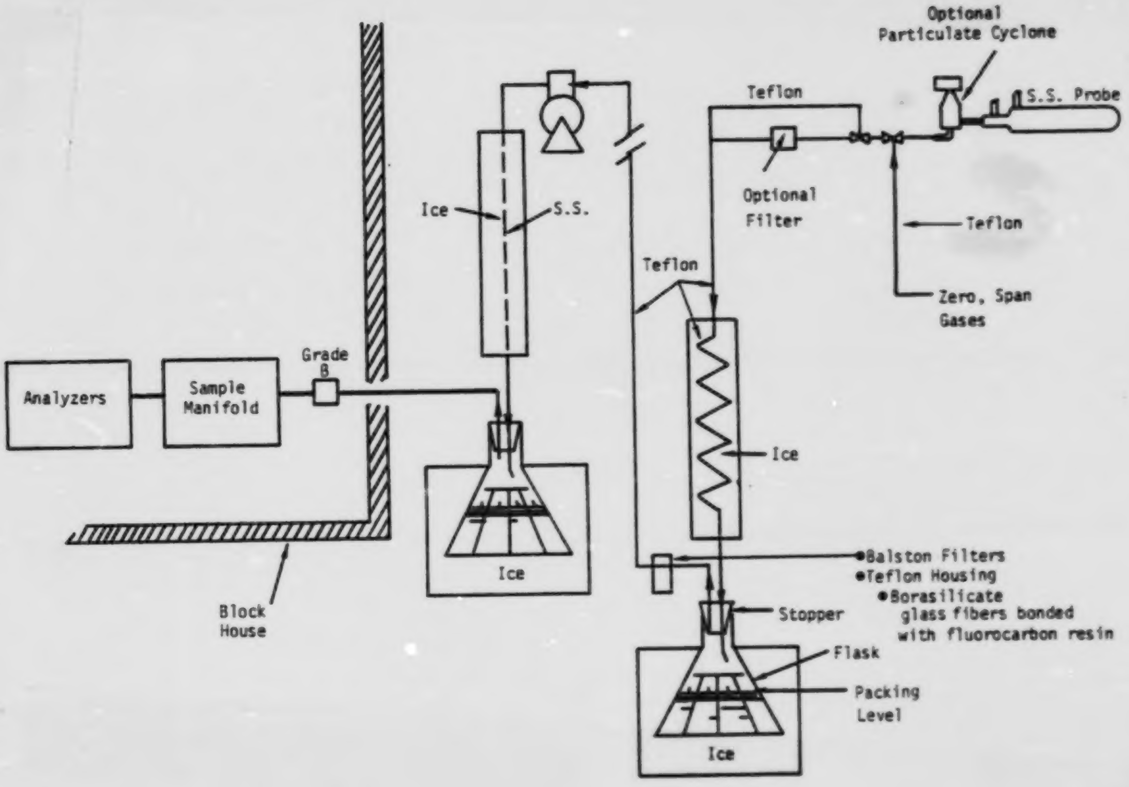

Optional
Particulate Cyclone
S.S. Probe
Teflon
Optional
Filter
Teflon
Zero, Span
Gases
Teflon
Ice
S.S.
Analyzers
Sample
Manifold
Grade
B
Ice
Ice
Block
House
●Balston Filters
●Teflon Housing
●Borasilicate
glass fibers bonded
with fluorocarbon resin
Stopper
Flask
Packing
Level
Ice

Figure 3-11. Exhaust Gas Sample Conditioning System.

of the NDIR and paramagnetic instruments as well as all the sample and sample bypass flowmeters. The pressure and flow sensing meters supplied with individual instruments are maintained at the manufacturers' specifications.

Stable combustion species are analyzed with state-of-the-art commercial instruments. A list of the species that are routinely measured, the analytical technique and the accuracy of the instruments at well-maintained conditions are also contained in Table 3-2. The continuous outputs are recorded on a multi-channel strip chart recorder. Other permanent recording and data reduction is performed with the on-line data logger and desk computer described earlier.

4.0 FUELS SELECTION

One of the major objectives of this program is the development of information relating the effects of differing coals on the operating and pollutant emissions characteristics of pulverized fuel (P.F.) combustors. This type of information will insure that the low NO_x burner development efforts of the EPA will be equally applicable to the wide range of coals that will be burned in the future. Since coals differ considerably in heating value, moisture content, ash, sulfur, nitrogen, etc., it is not surprising that the combustion characteristics differ from coal-to-coal. In fact, coal combustion characteristics differ so much that most power plants can only burn coals from selected mines, and still ensure both overall efficient electrical generation and maintenance of the air quality. Fuel selection, therefore, becomes a critical factor in the ability of industry to respond to the increased use of coals in utility and industrial furnaces and boilers throughout the U.S. It is imperative, therefore, that the fuels selected in this program do cover a broad range of characteristics in order to ensure the direct applicability of the results to industry and government needs in near as well as far term applications.

Since the program is projected to last three years, the general basis for the coals to be tested are:

- Year 1 — Coals which are well-characterized;
- Year 2 — Fuels projected for use in the near term; and
- Year 3 — Fuels of the future.

It is not the intent to select fuels solely on the basis of use by the utility industry, but to ensure that the fuels tested truly allow the development results to be generalized to the full range of fuels which might be burned in suspension.

Based on the above, the criteria used for the first year's fuel selection have been developed to satisfy the following objectives:

- The results of the tests should provide a basis whereby low emission coal burner technology can be generalized to indicate fuels which are currently or are projected to be used by the utility industry in the future.

- Small-scale and full-scale test results should provide the basis for a methodology whereby the environmental impact of coal combustion under low NO_x conditions can be assessed.
- The fuels tested should allow an understanding to be gained of the fate of trace compounds during combustion. Due to the program's focus this will be biased towards nitrogen, but consideration will also be given to sulfur and inorganic material.
- The scope of the tests should ensure that those coal characteristics which might produce operational difficulties under low NO_x conditions are identified.

The status of this effort is discussed first in terms of the impacts of fuel properties on pollutant production. The second section then defines the fuels selection criteria consistent with the first year's goals and then in the third section the results from Sections 1 and 2 form the basis for a general selection of fuels that fulfill these goals. In the final section the actual fuels that were obtained are described and related to the general fuels selection requirements to ensure that the full range of required fuels were actually acquired.

4.1 Pollutant Production and Coal Properties

It is neither possible nor desirable to test every coal being used at present or likely to be used in the future to demonstrate the capabilities of low NO_x burner concepts for a wide range of coals. Thus, the section of fuels to be tested is critical since the information gained must allow the performance of all coals to be assessed. An important factor in the choice of coals will be the type and amount of information available to date on the influence of coal properties and pollutant production. In this section of the report,data on the relationship between coal properties, pollutant formation and combustion performance are summarized with the major emphasis placed on this first year's effort upon nitric oxide production.

4.1.1 Coal Nitrogen and NO_x Formation

Nitrogen oxides are formed from the fixation of molecular nitrogen and from the oxidation of nitrogen bound in the fuel. Under uncontrolled conditions fuel NO formation accounts for greater than 75 percent of the total NO_x produced in coal flames. The development of low NO_x combustors for coal has tended to proceed along a single path – the production of a fuel-rich primary zone to maximize N_2 production. Consequently, the fate of coal nitrogen during the heat release process is of vital importance and there have been several laboratory studies on this subject. Development testing to date has concentrated upon the attainment of low NO_x with very little attempt to assess the impact of coal properties on the development program. Field tests have been carried out with a wide variety of fuels, but differences in hardware probably mask any influence of the fuel. This section reviews information available to date from these three types of studies.

Laboratory-Scale Investigations

Two investigations, those of Axworthy(4.1) and Blair et al.(4.2) have been concerned with the pyrolysis products of coals. Axworthy has used both single and two-stage quartz reactors to study the pyrolysis of coals under both inert and oxidative conditions. Table 4-1 lists HCN yields from coals resulting from inert pyrolysis with the pyrolysis reactor maintained at 1100°C. It should be noted that percentage yield of HCN varies by almost a factor of 2 for the various coals tested. The COED gasification char is a low volatile, but relatively high nitrogen solid and as could be expected, the yield of HCN at these low temperatures is low since the solid has already been processed at similar temperatures. Figure 4-1 shows the HCN yield for the Pittsburgh coal in a two-stage pyrolysis reactor as a function of the temperature of the first stage with the second stage reactor maintained at 1100°C. In earlier studies it had been shown that there was almost quantitative conversion of the nitrogen in model compounds (pyridine and benzonitrile) to HCN at 1100°C. Thus, it can be assumed that volatile nitrogen compounds

Table 4-1. HCN Yields from Inert Pyrolysis of Coals at 1100°C (after Axworthy$^{(4.1)}$)

Coal*	% Nitrogen (as received)	% HCN Yield
Pittsburgh No. 8$^{(1)}$	1.2	23.6 ± 1.5
Montana Lignite - A$^{(7)}$	0.61	23.8 ± 1.6
COED Char$^{(18)}$	0.99	1.7 ± 0.1
Bituminous Coal$^{(19)}$	1.17	30.0
Bituminous Coal$^{(20)}$	1.8	24.5
Montana Coal$^{(3)}$	0.93	16.8 ± 0.3

*Coals will be identified by a superscript and all relevant properties are given in Appendix A.

evolved in the first stage reactor are converted to HCN in the second stage. The data presented in Figure 4-1 indicates that nitrogen compounds other than HCN are evolved from the coal at lower temperatures. With the first and second stages of the pyrolysis reactor at 750°C the HCN yield was only 7 percent (see Figure 4-1). However, the yield was increased to 22 percent when the temperature of the second pyrolysis reactor was raised to 1100°C. This suggests that the conditions in the first stage produce nitrogen compounds which will undergo further pyrolysis at higher temperatures producing HCN. Axworthy$^{(4.3)}$ has also compared the HCN yield from coals 1, 19, and 20 with the first stage at 600°C and the second stage at 1100°C. The yields were 74.5, 36.7, and 51.8 percent of the single stage yield at 1100°C. These results suggest that there can be considerable differences in the rate of fuel nitrogen evolution from different coals at lower temperatures. Coal 1 is from the U.S., coal 19 is from Germany, and coal 20 was mined in England.

F 4-1

In another experiment with similar objectives, Blair et al.$^{(4.2)}$ measured the species evolved from a single coal particle and the rate of mass

19

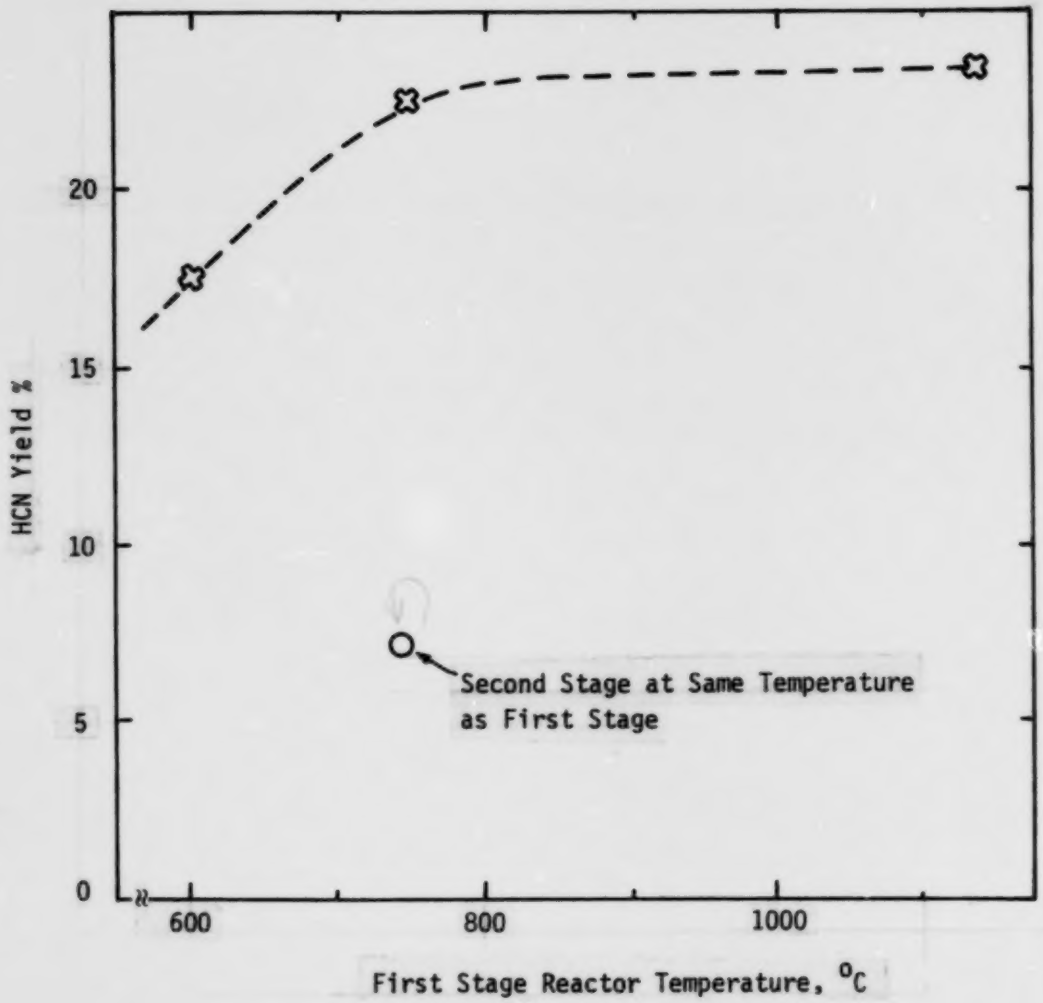


Figure 4-1. HCN Yield from Pittsburgh No. 8(1) Coal under Inert Two-Stage Pyrolysis Conditions (after Axworthy 4.1)

evolution as a function of temperature, heating rate and coal composition. Coal pyrolysis was accomplished by using: a) a platinum ribbon whose heating rate could be controlled up to 20°C/msec and uncontrolled at rates of up to 75°C/msec in a helium atmosphere maintained at 200-250°C; and b) a graphite ribbon in an argon atmosphere. Heating rates were uncontrolled with the graphite ribbon at a given temperature. Three coals were investigated (Arkwright[8], Wyodak[9] and Illinois No. 6[10]) and it was found that:

- the total mass evolved as a function of pyrolysis temperature is much more dependent upon coal type than is the nitrogen evolution. Also, nitrogen evolution is much more sensitive to temperature than is the total mass evolution (see Figure 4-2);
- Table 4-2 shows the fraction of coal nitrogen converted to HCN, NH_3, N_2 and high boiling point compounds as a function of final pyrolysis temperature. High boiling point compounds account for approximately the same fraction as does HCN and the sum of the nitrogen detected is less than half of the nitrogen lost, suggesting that a large fraction of the nitrogen evolved is in intermediate boiling range compounds. The results presented in Table 4-2 indicate some scatter. HCN yields of 6 percent and 12 percent are shown for maximum temperatures of 1400°C for the same coal. This variation could be due to differences in the composition of separate coal particles or because the particle heating rate is uneven because of particle movement;
- nitrogenous species appear to be evolved late in the volatilization sequence.

The major difference in the experiments of Axworthy and Blair is that there is the possibility of secondary pyrolysis in the experimental system used by Axworthy. Indeed, Axworthy uses this secondary pyrolysis in

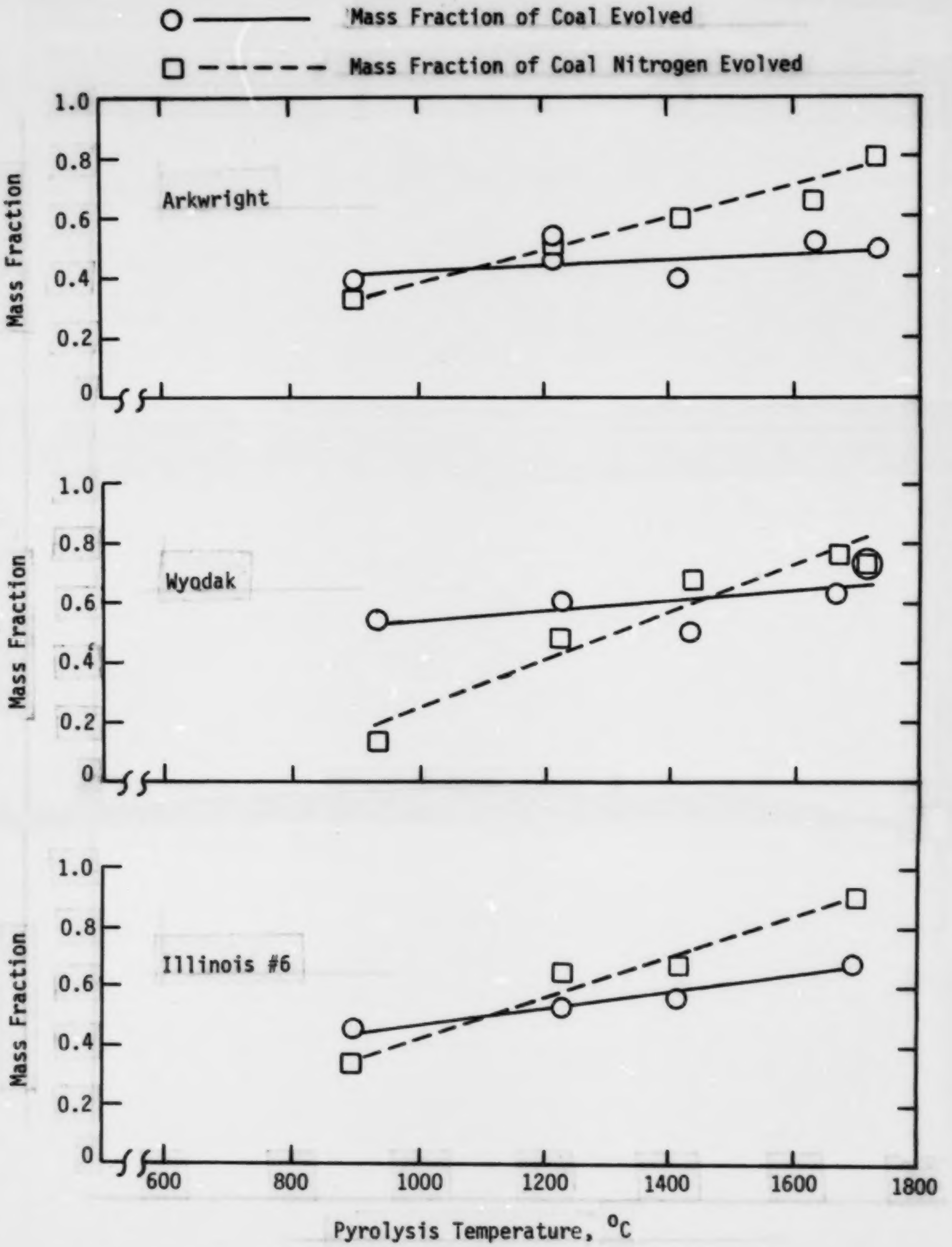


Figure 4-2. Mass Fraction Evolved as a Function of Temperature.

Table 4-2. Percent of Coal Nitrogen Evolved as HCN, NH_3, N_2 Compounds with a Boiling Point Greater than 750°C (Collected on Glass Wool)(4.2)

Pyrolysis Conditions				Percent of Fuel Nitrogen Converted to			
Coal	Max Temp. °C	Pyrolysis Interval Sec.	Heating Rate °C/ms	HCN	NH_3	N_2	High Boiling Compounds
Arkwright	1400	10	20		–	–	4.08
Wyodak	1400	10	20	15.0	–	–	11.8
Arkwright	1400	10	20	6.11	–	–	3.86
Arkwright	1000	10	20	2.64	–	–	2.64
Arkwright	1400	10	20	12.0	–	–	11.8
Wodak	1000	10	20	1.88	–	–	5.28
Arkwright	1400	10	20	–	2.63	–	–
Wyodak	1400	10	20	–	3.43	–	–
Arkwright	1350	10	20	–	–	1.0	–
Arkwright	1350	10	20	–	–	0.72	–
Arkwright	1350	10	20	–	–	2.2	–
Arkwright	350	10	20	–	–	0.065	–
Wyodak	1350	10	20	–	–	0.31	–
Wyodak	350	10	20	–	–	0.26	–

the two-stage experiments as a means of measuring "reactive nitrogen". It also appears that the primary pyrolysis nitrogen product will be rapidly converted to HCN regardless of the form.

Soloman$^{(4.4)}$ has used an automated heated grid devolatization apparatus which allows extensive analysis of gas, tar and char produced during devolatilization and yields almost complete mass and elemental balances. The potential drawback of the heated grid seems minimal since the products appear unperturbed by the grid. The major portion of the experiments were carried out under vacuum which appears to minimize secondary reactions. The apparatus uses an electrically-heated grid of the kind described by Anthony et al.$^{(4.5)}$. The coal is brought to temperature at a nominal heating rate of 600°C/sec, held at temperatures from 300 to 1000°C for between 5 and 80 sec and then cooled. Measurements are made of particle temperature, the elemental composition and mass distribution of the products and the concentration of components in the gas. Solomon has reported the devolatilization behavior of nine coals ranging in rank from lignite to high volatile A bituminous (Nos. 21 through 29 in Appendix A).

Solomon found that in vacuum devolatilization there is a high tar yield with a very similar elemental composition as the parent coal. This suggests that the tar is produced by the release of random clusters from the coal molecule without substantial secondary reactions. The major products of devolatilization appear to be released in independent parallel processes. At the lowest temperature, tars, CO_2 and H_2O are released. At intermediate temperatures methane and other hydrocarbons are evolved. CO and H_2 are released over a wide range of temperatures. The evolution of oxygen-containing products is related to the concentrations of oxygen functional groups in the coal. Figure 4-3 shows the weight percentage of nitrogen in the components, char, tar and gas, for two coals. The gas nitrogen is determined by difference, but it appears that very little nitrogen is released into the gas at low temperatures (measurement of HCN and NH_3 in the gas showed levels of less than 0.1 percent). Figure 4-4$^{(4.4)}$ shows the distribution of nitrogen between the three components for some representative coals. The concentrations are normalized

F-4-3

F-4-4

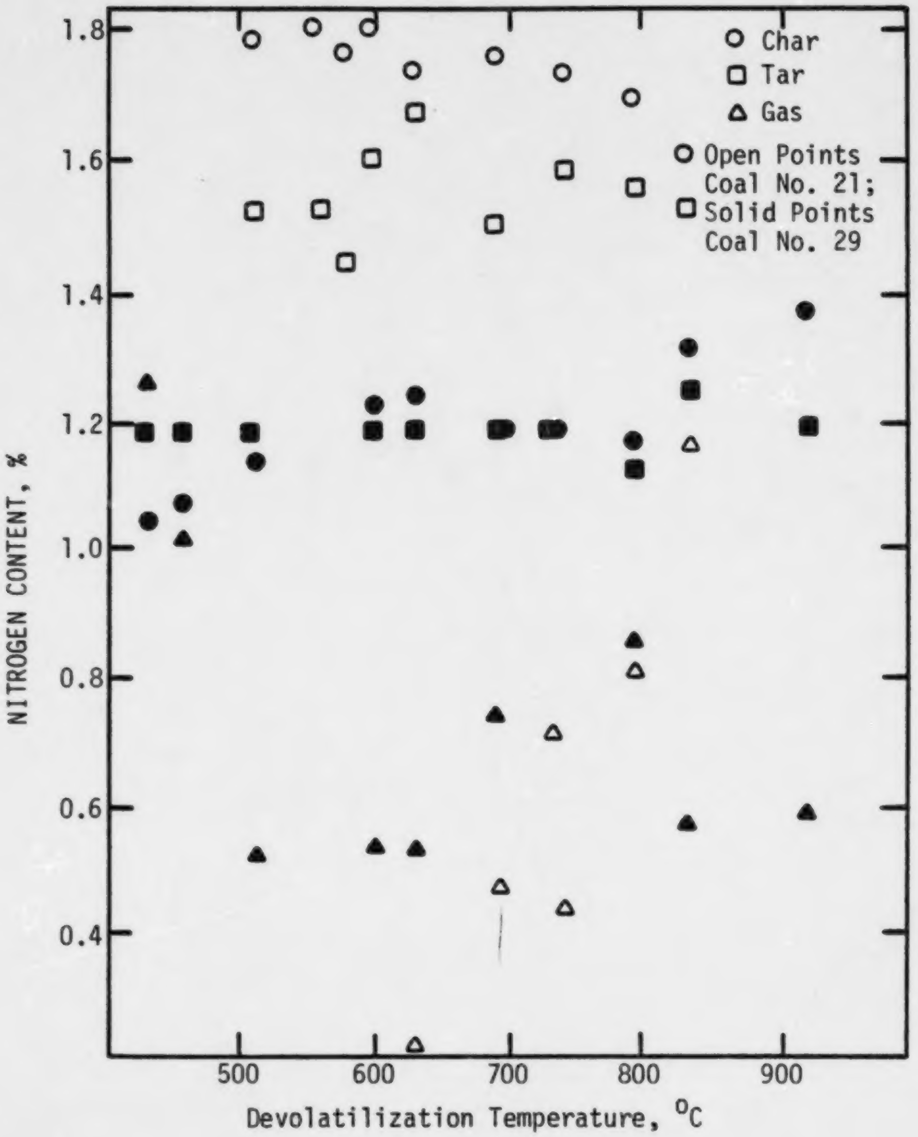


Figure 4-3. Nitrogen Content of Tar, Char, and Gas as a Function of Devolatilization Temperature (after Solomon (4.4)).

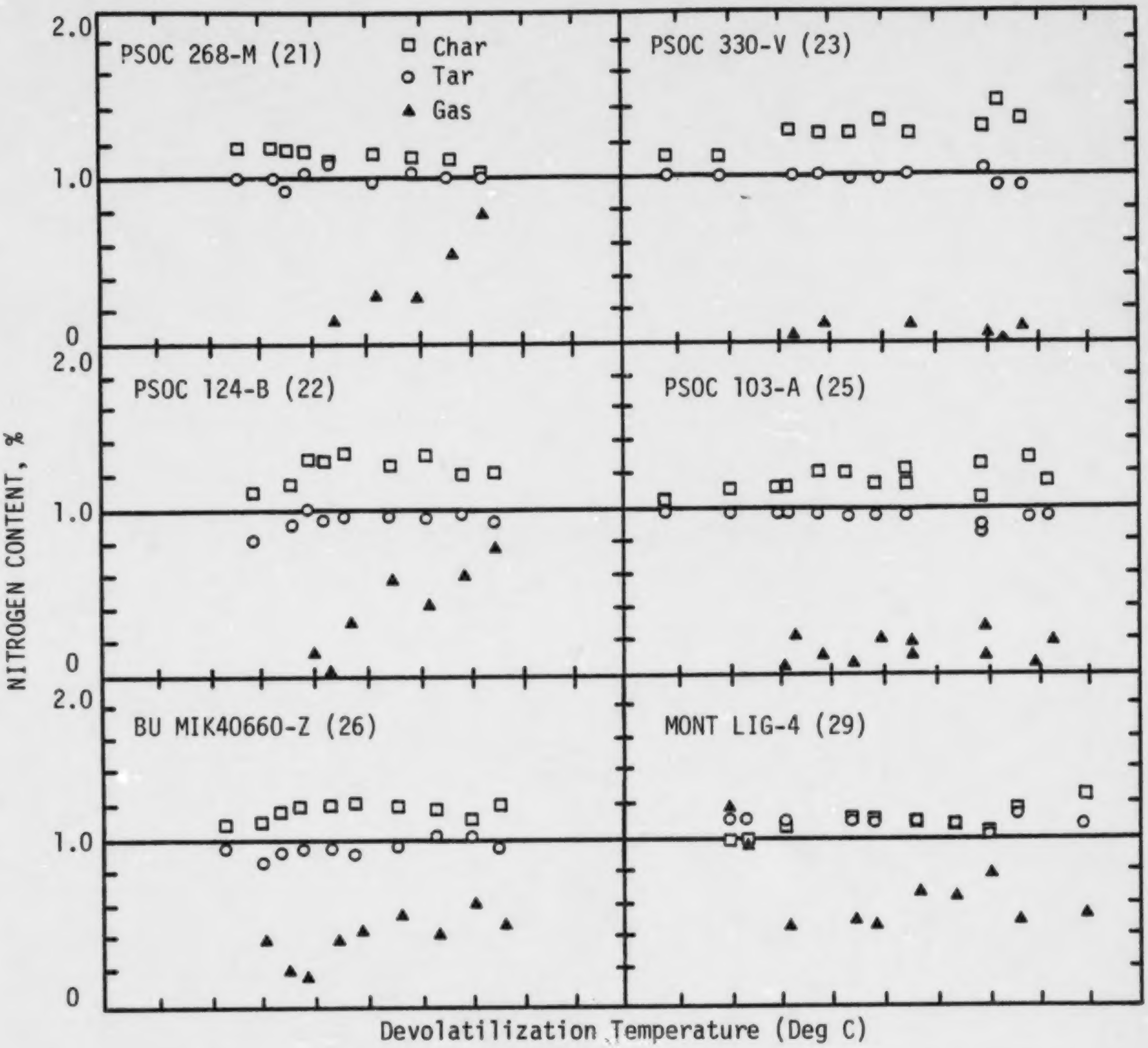


Figure 4-4. Nitrogen Distribution in Devolatilization Products: Percentage of Nitrogen in Char, Tar, and Gas Normalized to that in the Parent Coal vs. Devolatilization Temperature.

to the level of nitrogen in the parent coal. It can be seen that the tar nitrogen content is similar to that of the parent coal supporting the argument that the tar structure is similar to that of the coal. Nitrogen contained in ring structures will also appear in the char. The char nitrogen content is higher than the parent coal. The experiments were mainly limited to temperatures below 800°C and there was little evidence of a reduction in the char nitrogen level, although there is a continual reduction of the mass of nitrogen retained in the char as the devolatilization temperature increases.

The percentage of char and tar on a dry mineral matter-free basis as a function of devolatilization temperature is given in Figures 4-5 and 4-6 for four coals. For all the coals on which data tables are presented in Ref. 4.4 it appears that there is a change in rate of weight loss as a function of temperature around 600°C. This effect is less apparent for the lignite coal. Figure 4-7 compares the fraction of coal nitrogen retained in the char for the four coals. Even accounting for some experimental error it is apparent that the four coals have different char nitrogen retention characteristics. With the lignite coal there is very little difference in char nitrogen for temperatures between 700 and 840°C. The experimental data for the other two coals (numbers 21 and 24) show a much more continous decrease of nitrogen content with pyrolysis temperature.

F 4-5
4-6

F 4-7

The experimental results of Blair et al.(4.2) and Solomon(4.4) are in qualitative agreement in that both experiments indicate that nitrogen is evolved from the coal in some intermediate boiling point compounds rather than as HCN or NH_3. If Axworthy's experiment is viewed as a measure of the volatile nitrogen that can be converted to HCN it appears that the tar 'nitrogen' can also be considered in two fractions. Upon heating, the original coal breaks into three components:

- char with a higher nitrogen content than the parent coal;
- tar with a similar nitrogen content to the parent coal; and
- gases with a low nitrogen content which appears to increase as temperature increases.

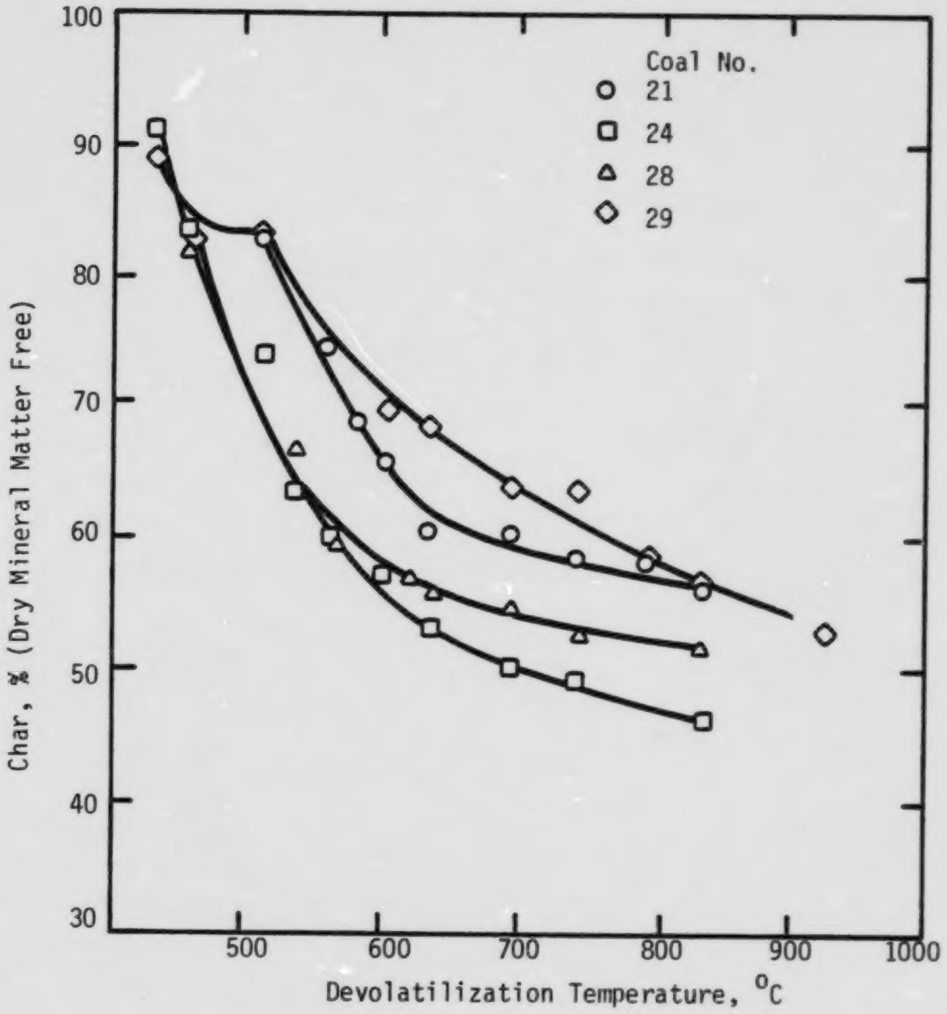


Figure 4-5. Char Percentage as a Function of Devolatilization Temperature (After Soloman 4.4).

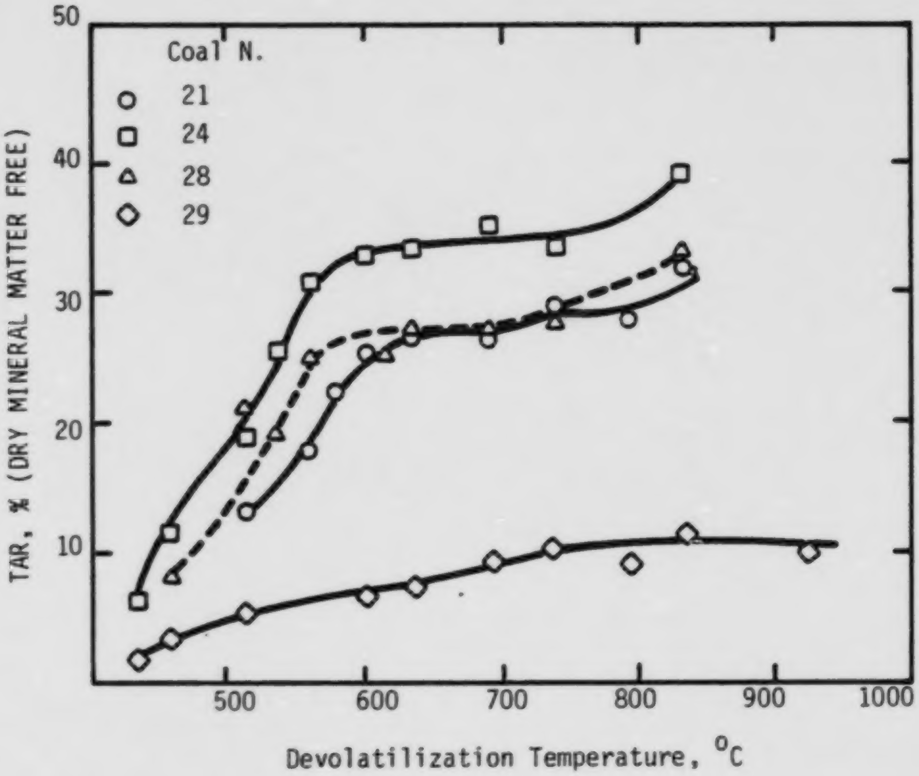


Figure 4-6. Tar Percentage as a Function of Devolatilization Temperature (after Soloman 4.4).

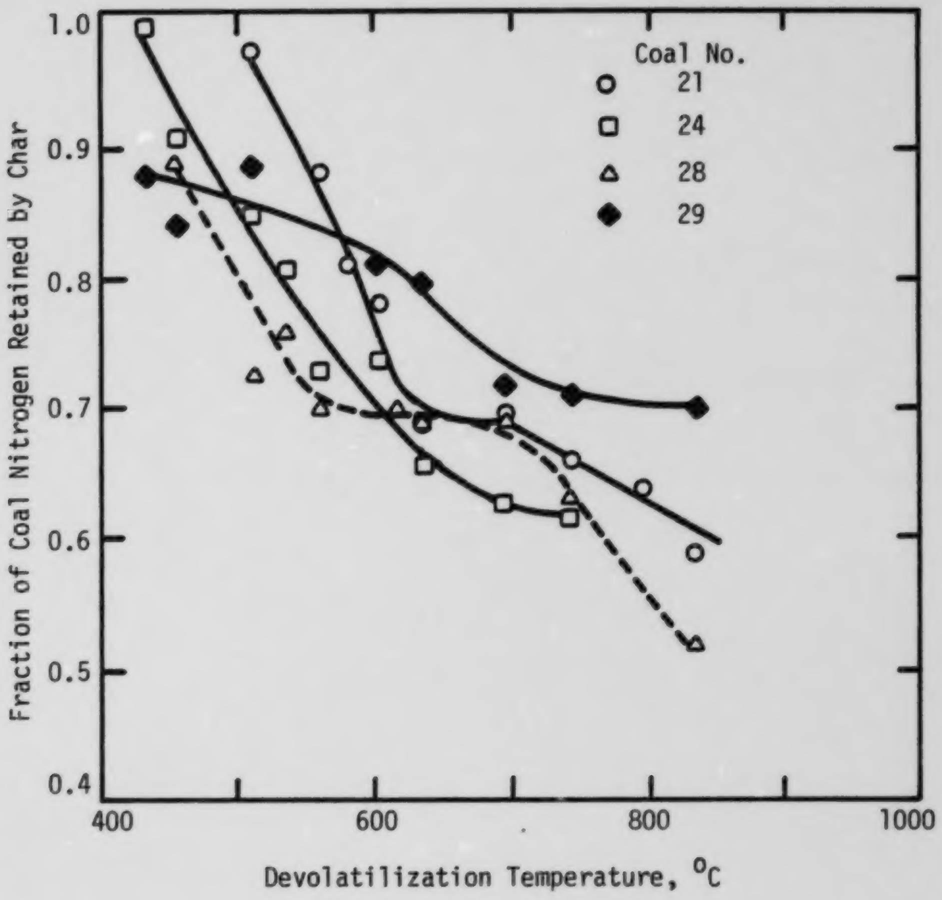


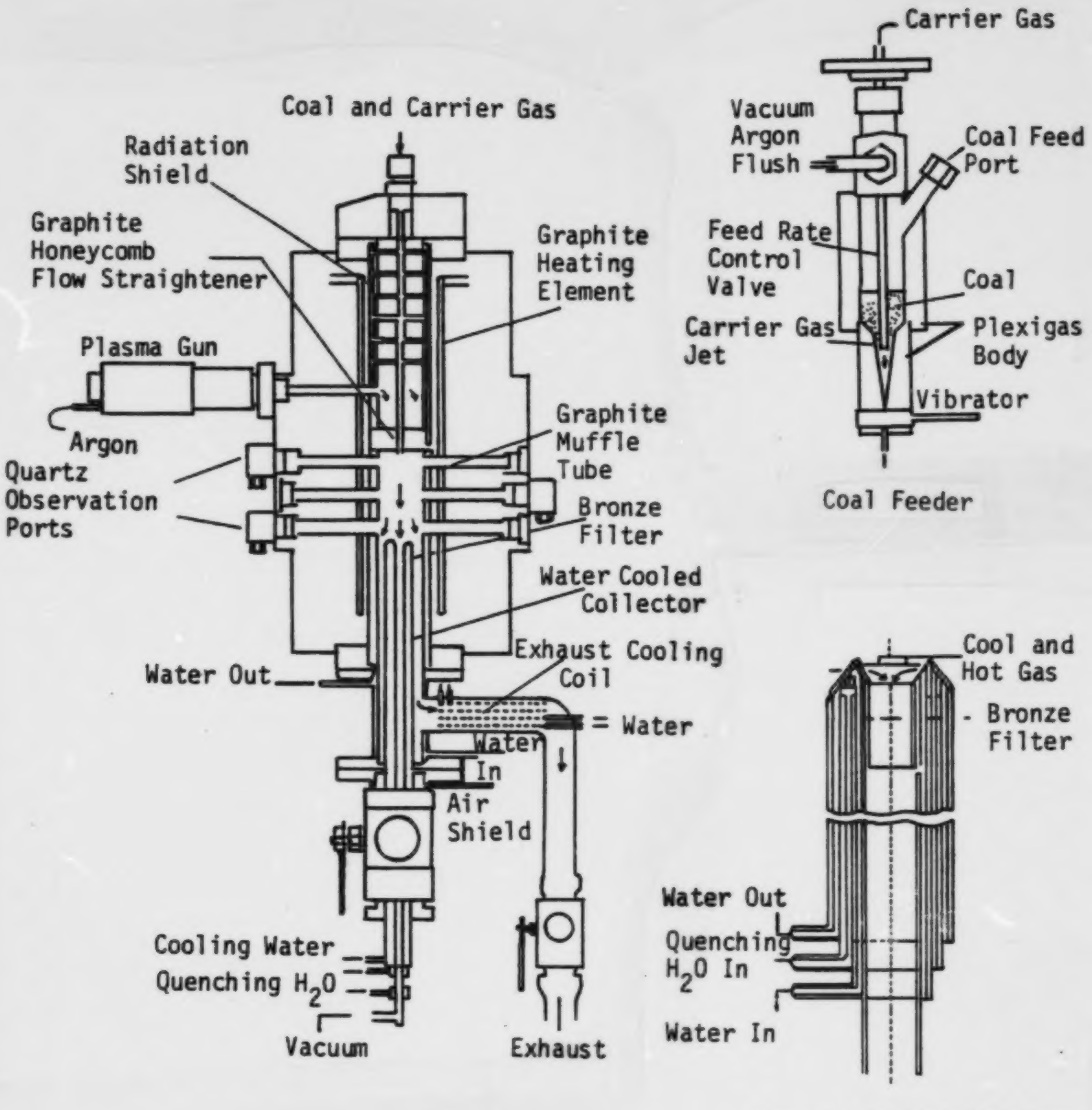
Figure 4-7. Fraction of Coal Nitrogen Retained in the Char (after Soloman 4.4).

In Axworthy's experiment secondary reactions will take place and it appears that the tar fraction is divided once more into two components, one of which cannot be pyrolyzed to HCN. The results reported earlier from Axworthy suggest that secondary reactions will produce a "tar char" which contains about 25 percent of the coal nitrogen.

For some time Sarofim and co-workers at MIT(4.6) have been conducting a study to characterize the kinetics of pyrolysis and oxidation of the nitrogen content of coal under well-controlled laboratory conditions simulating the range of temperatures and heating rates expected in coal combustors. Heating rates are on the order of 10^5 to 10^6 °C/sec and maximum temperatures in large scale pulverized coal flames are unlikely to exceed 2200°K. Two electrically heated resistance furnaces were used in Sarofim's studies. For short residence times (5 to 300 milliseconds) the coal was injected with argon through a 1.2 mm I.D. water-cooled tube along the furnace axis. A preheated inert or oxidizing stream is fed to the working section of the furnace through an alumina flow straightener and the coal particles are heated both by convection from this stream and by radiation from the furnace walls. Then the solid particles are collected in a probe which utilizes an argon quench. The furnace is operated in a "free fall" mode where the probe is removed and a water-cooled section added to the bottom of the furnace (see Figure 4-8). The particles are then allowed to fall through the cooled section onto a bronze disc collector. In addition, experiments were conducted in which the coal was heated slowly to furnace temperatures in a crucible. Experiments were performed under oxidizing conditions with helium/oxygen mixtures. Approximately 15 percent of the stoichiometric oxygen requirements were fed with the coal through the water-cooled injector producing a diffusion flame stabilized at the injector.

F4-8

The coals used in these experiments were among those investigated by Axworthy, coal No. 6 a Pittsburgh Seam, No. 8 R.V.A. bituminous coal from the Ireland mine and coal No. 7 a Montana lignite A from the Savage mine which should be similar to coal No. 29 used by Solomon. In a new grant (R805552), five other coals are to be studied (Nos. 1, 2, 3, 17 and 34 in


Coal and Carrier Gas
Radiation Shield
Graphite Honeycomb Flow Straightener
Graphite Heating Element
Plasma Gun
Argon
Quartz Observation Ports
Graphite Muffle Tube
Bronze Filter
Water Cooled Collector
Water Out
Exhaust Cooling Coil
= Water
Water In
Air Shield
Cooling Water
Quenching H_2O
Vacuum
Exhaust
Carrier Gas
Vacuum Argon Flush
Coal Feed Port
Feed Rate Control Valve
Coal
Carrier Gas Jet
Plexigas Body
Vibrator
Cool and Hot Gas
Bronze Filter
Water Out
Quenching H_2O In
Water In

Coal Feeder

Water Cooled Collector

Figure 4-8. Laminar Flow Furnace System

Appendix A). Sarofim suggests that the crucible experiment represents the asymptotic values associated with inert pyrolysis. On the basis of comparison made from data presented in Figures 4-9 and 4-10 (Ref. 4.6), Lanier$^{(4.7)}$ has pointed out that there are inconsistencies in the data. At low temperatures nitrogen retention for free-fall experiments of one second duration with temperatures below 1200°K appears to be less than that with crucible experiments which should be representative of an infinite residence time (see Figure 4-11). However, examination of more recent crucible data which compares the nitrogen retention of five coals as a function of furnace temperature provides an explanation (see Figure 4-12) for this apparent anomaly. It can be seen that all five coals behave in a similar manner (only one coal is markedly different from the other four) and that there is very little nitrogen weight loss between 1000°K and 1200°K. Thus, the shape of the curve shown in Figure 4-9 would probably have been drawn differently if more data were available. It might well include a sharp discontinuity at temperatures between 1200°K and 700°K for nitrogen retention. This type of step function behavior is also observed in the experiments of Solomon discussed earlier (see Figure 4-7). Sarofim's results agree with the observation of Blair et al. - in that weight loss occurs before nitrogen compounds are evolved from the coal.

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F-4-11

F-4-12

Sarofim and co-workers have used a simplified scheme to represent the fate of coal nitrogen during combustion. This scheme is summarized in Figure 4-13 and the overall conversion of coal nitrogen to nitric oxide "n*" is given by

F-4-13

$$n^* = \alpha\eta_1 + (1 - \alpha)\gamma\,\eta_2$$

were:

α = fraction of coal nitrogen released as volatiles

$1 - \alpha$ = fraction of nitrogen retained in char

η_1 = fraction of volatile nitrogen converted to NO_x

γ = fraction of char nitrogen consumed

$\gamma\eta_2$ = fraction of char nitrogen converted to NO_x

Information obtained from oxidation experiments allows the values of η_1 (the volatile nitrogen conversion efficiency) and $\alpha\eta_1/\eta^*$ (the percentage contribution of volatile nitrogen to the total nitric oxide production)

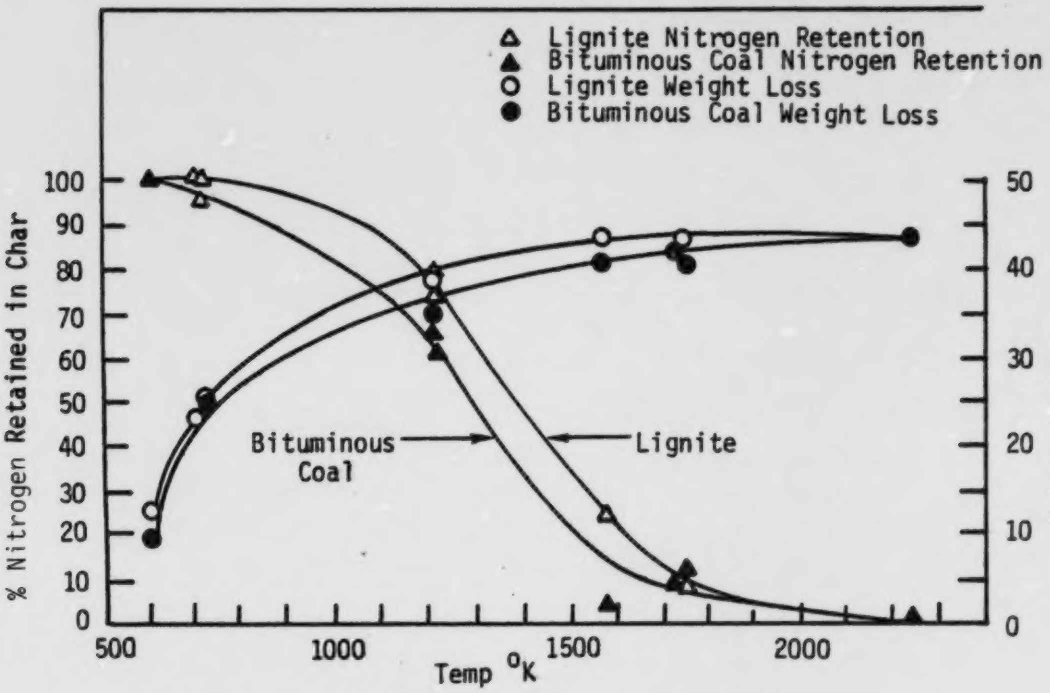


Figure 4-9. Nitrogen Retention in Char and Weight Loss (Dry) for Coal Heated in Crucibles.

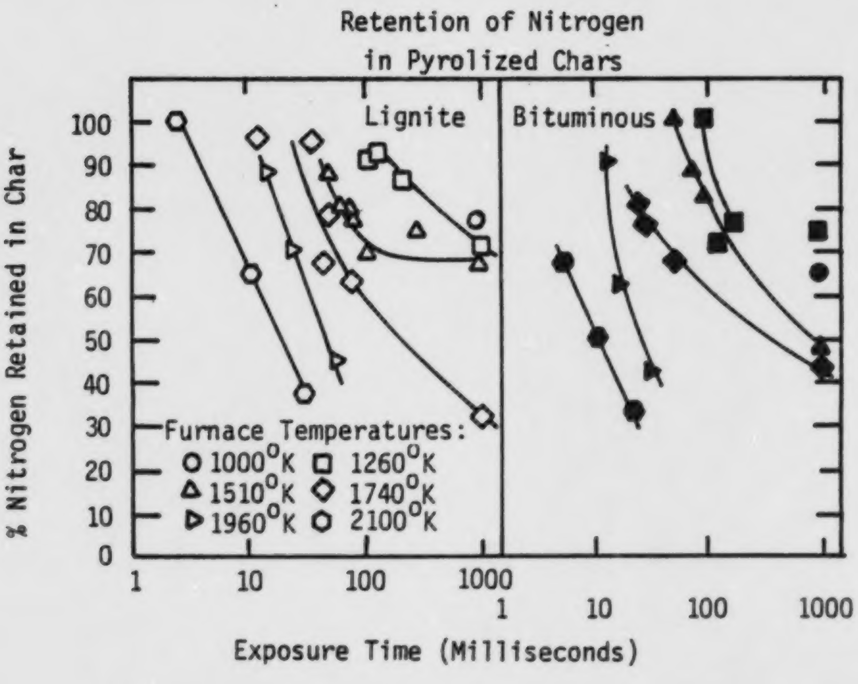

Retention of Nitrogen in Pyrolized Chars

Figure 4-10. Retention of Nitrogen in Char Versus Time.

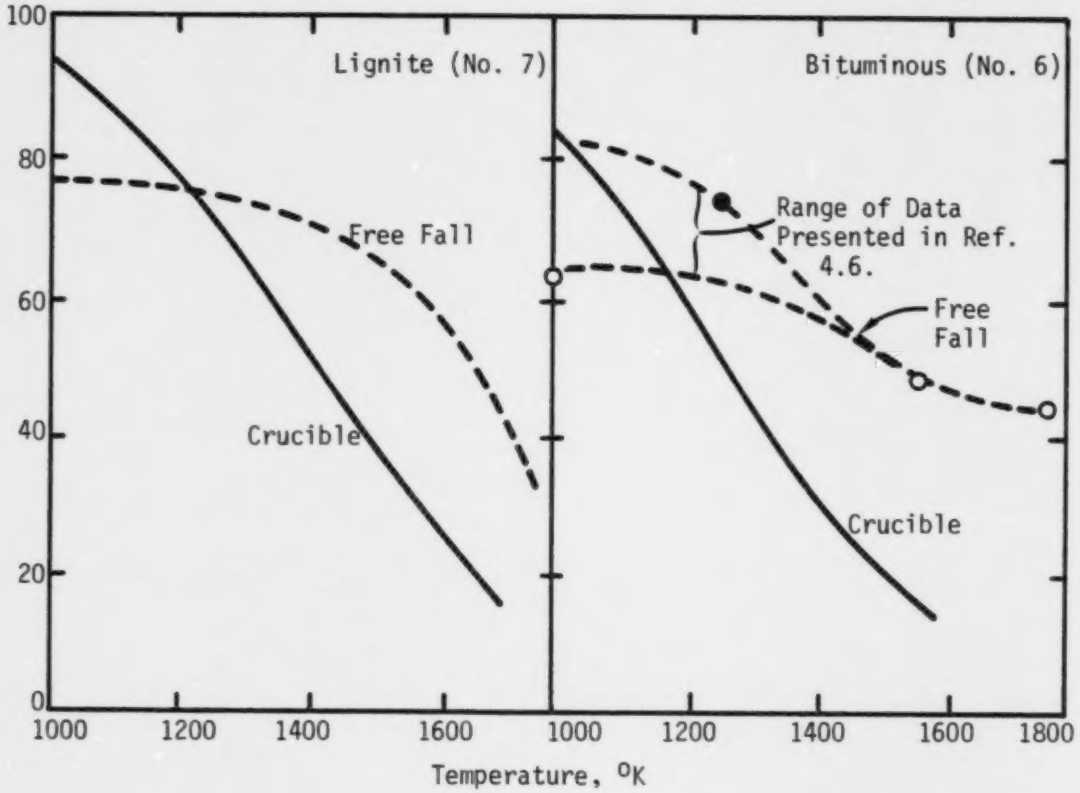


Figure 4-11. Comparison of Nitrogen Retention for Free-Fall and Crucible Experiments (After Pohl and Sarofim 4.6).

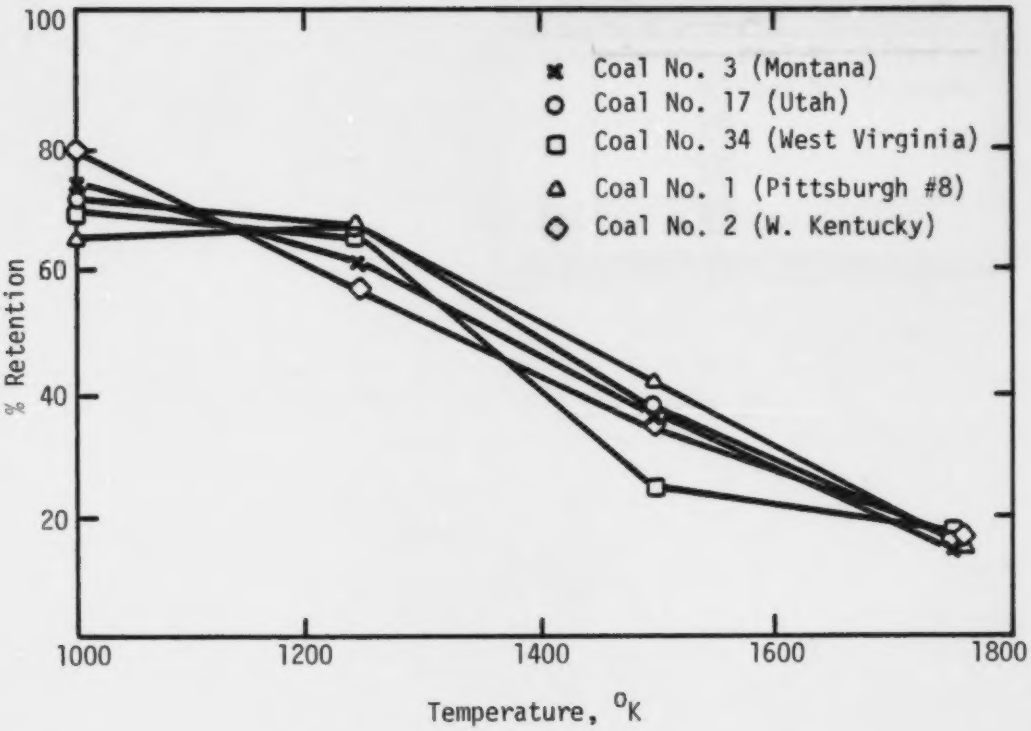
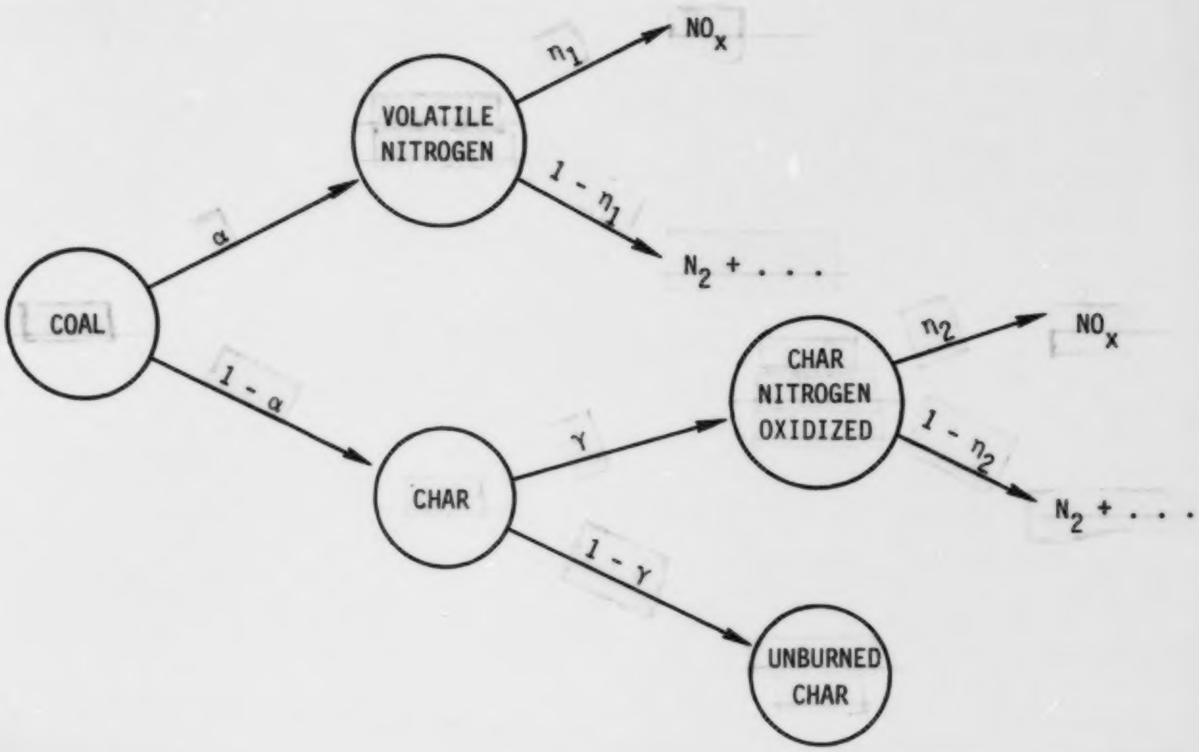


Figure 4-12. Percent Nitrogen Retention of Various Coals Crucible Experiments (Ref. 4.5).



COAL
α
$1 - \alpha$
VOLATILE NITROGEN
η_1
NO_x
$1 - \eta_1$
$N_2 + . . .$
CHAR
γ
$1 - \gamma$
CHAR NITROGEN OXIDIZED
η_2
NO_x
$1 - \eta_2$
$N_2 + . . .$
UNBURNED CHAR

α = fraction of coal nitrogen released as volatiles
$1 - \alpha$ = fraction of nitrogen retained in char
η_1 = fraction of volatile nitrogen converted to NO_x
γ = fraction of char nitrogen consumed
$\gamma\eta_2$ = fraction of char nitrogen converted to NO_x

Figure 4-13. Simplified Scheme Showing Fate of Fuel Nitrogen (after Sarofim 4.9)

to be determined. A cross plot of calculations made using this model from two different references is presented in Figure 4-14 for lignite (No. 7). The earlier data due to Pohl and Sarofim(4.6) was obtained with a furnace temperature of 1500°K and clearly indicated that the conversion efficiency of char nitrogen to NO was less than the conversion efficiency of the parent coal. More recent data reported by Song, Beér and Sarofim(4.9) is not so clear. Figure 4-15 shows data taken from both sources. At 1750°K char nitrogen conversion to NO is higher than coal nitrogen for fuel equivalence ratios greater than 0.7. At 1250°K the curves presented in Figure 4-15 do not intersect before an equivalence ratio of one. In these experiments the fuel is injected with oxygen/helium mixtures and oxidation takes place in a diffusion flame. Thus, evaluation of these results might well be complicated because of variations in mass transfer effects.

Pershing(4.10, 4.11, 4.12) carried out a series of laboratory flame reactor experiments at the University of Arizona with coals Nos. 1, 2, 3 and 4. In these experiments the details of the fuel/air contacting process have a profound influence upon the conversion of coal nitrogen to NO in flames. Argon replaced molecular nitrogen in the oxidant to eliminate thermal NO production and two methods of fuel injection were used to vary the rate of fuel/air mixing. Rapid fuel/air mixing was achieved by using divergent coal injection in contrast to axial fuel injection which gives a much reduced mixing rate. The conversion of fuel nitrogen to NO for five different solid fuels is shown in Figure 4-16 as a function of fuel nitrogen content and method of fuel injection. For the four coals studies, the major effect was the rate of fuel/air mixing. This is in contrast to the char (No. 18), where fuel nitrogen conversion to NO is almost insensitive to the rate of fuel/air mixing. If the coals tested by Pershing do, in fact, represent a wide range in properties, then it appears that fuel properties do not have a very significant influence upon fuel NO formation. The Pittsburgh and Colorado coals (Nos. 1 and 4) have very similar nitrogen contents (dmmf) and yet there is a differnece in fuel NO production. The effect of O_2/N_2 ratio on coal

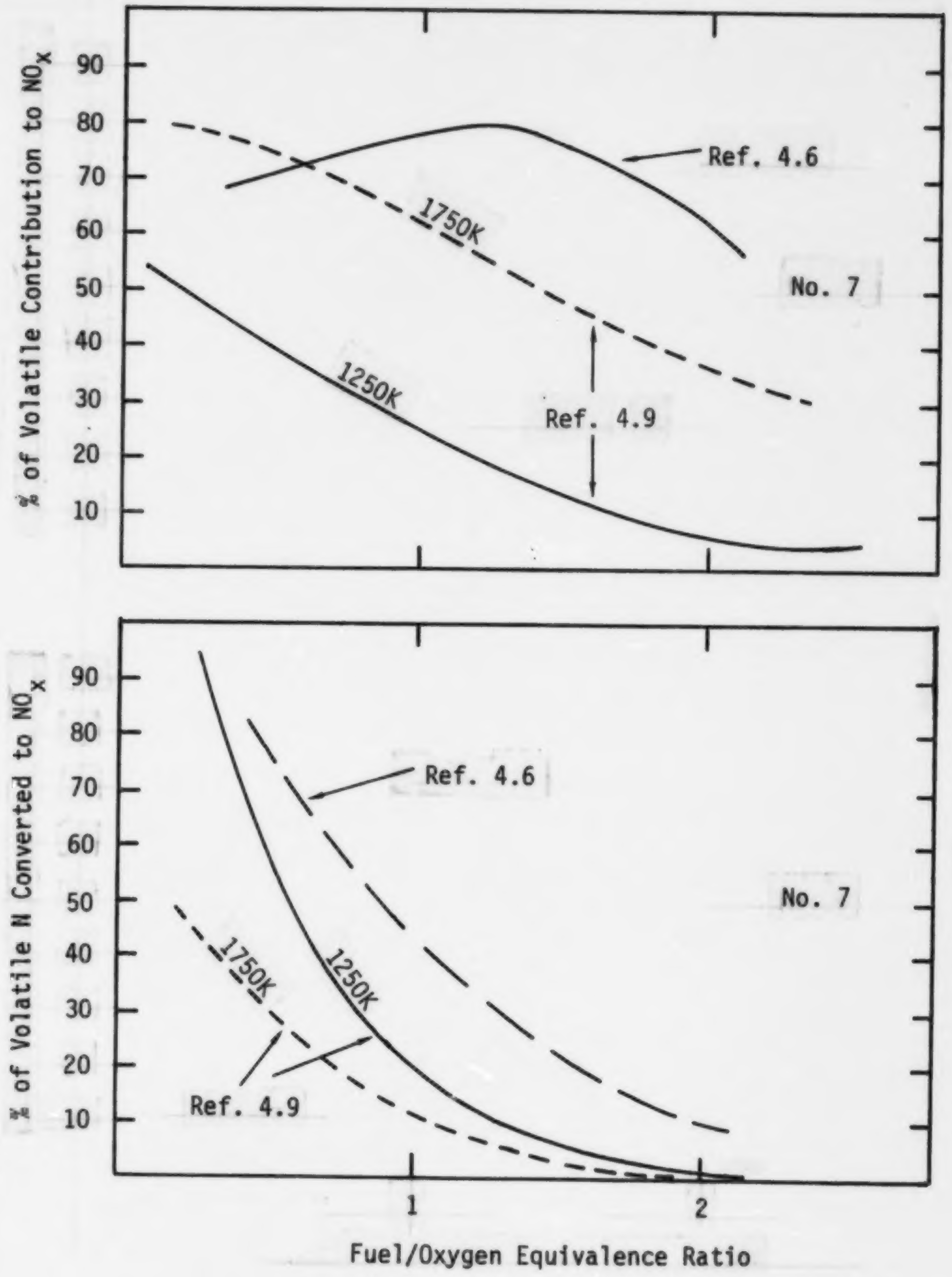


Figure 4-14. Contribution of Volatiles to NO_x Emission: Total NO_x Contributed by Volatiles (Top), and Conversion of Volatiles to NO_x (Bottom) (Refs. 4.6 and 4.9).

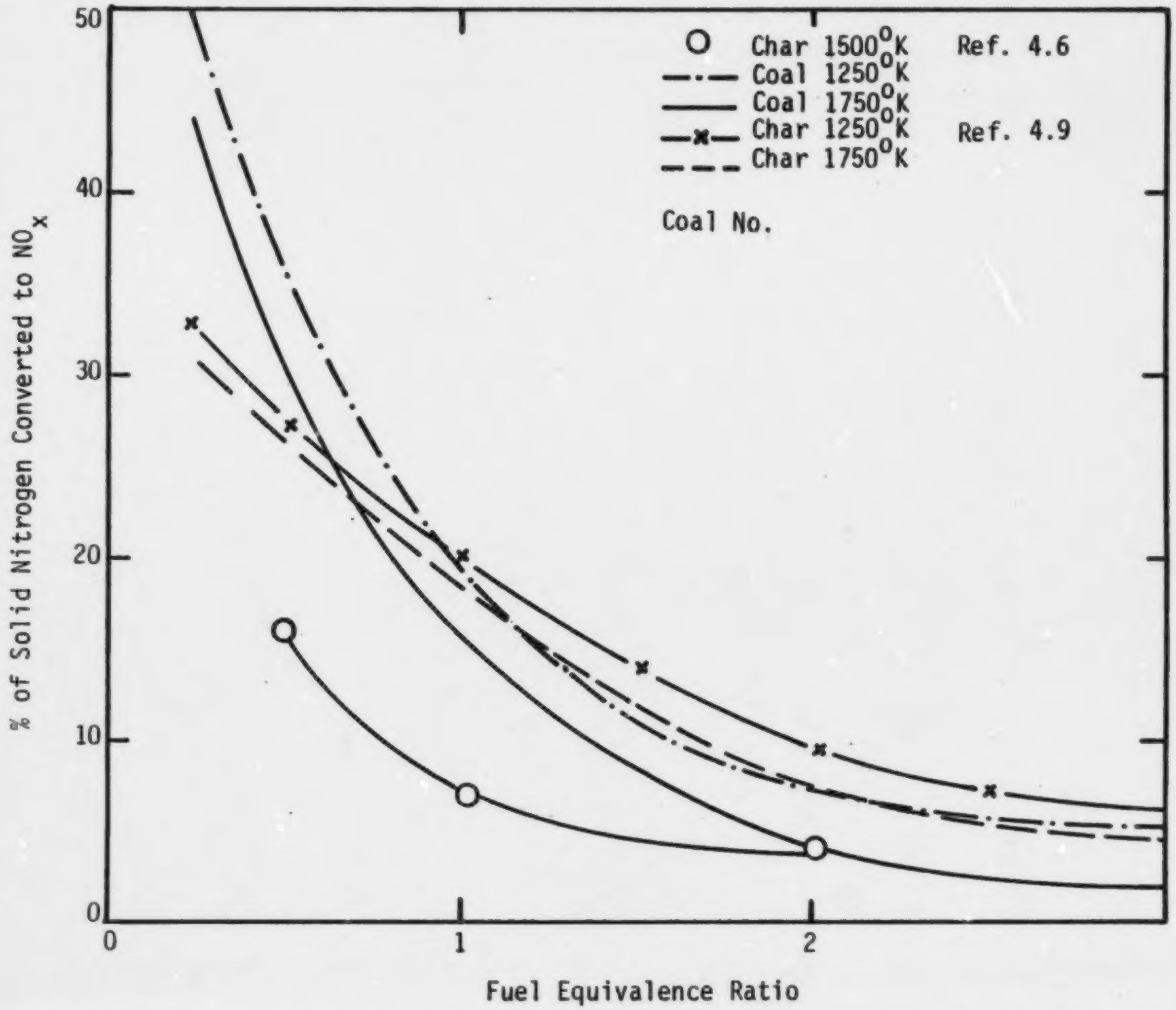


Figure 4-15. Comparison of NO Production from Char and the Parent Coal (after Sarofim[(4.8)]).

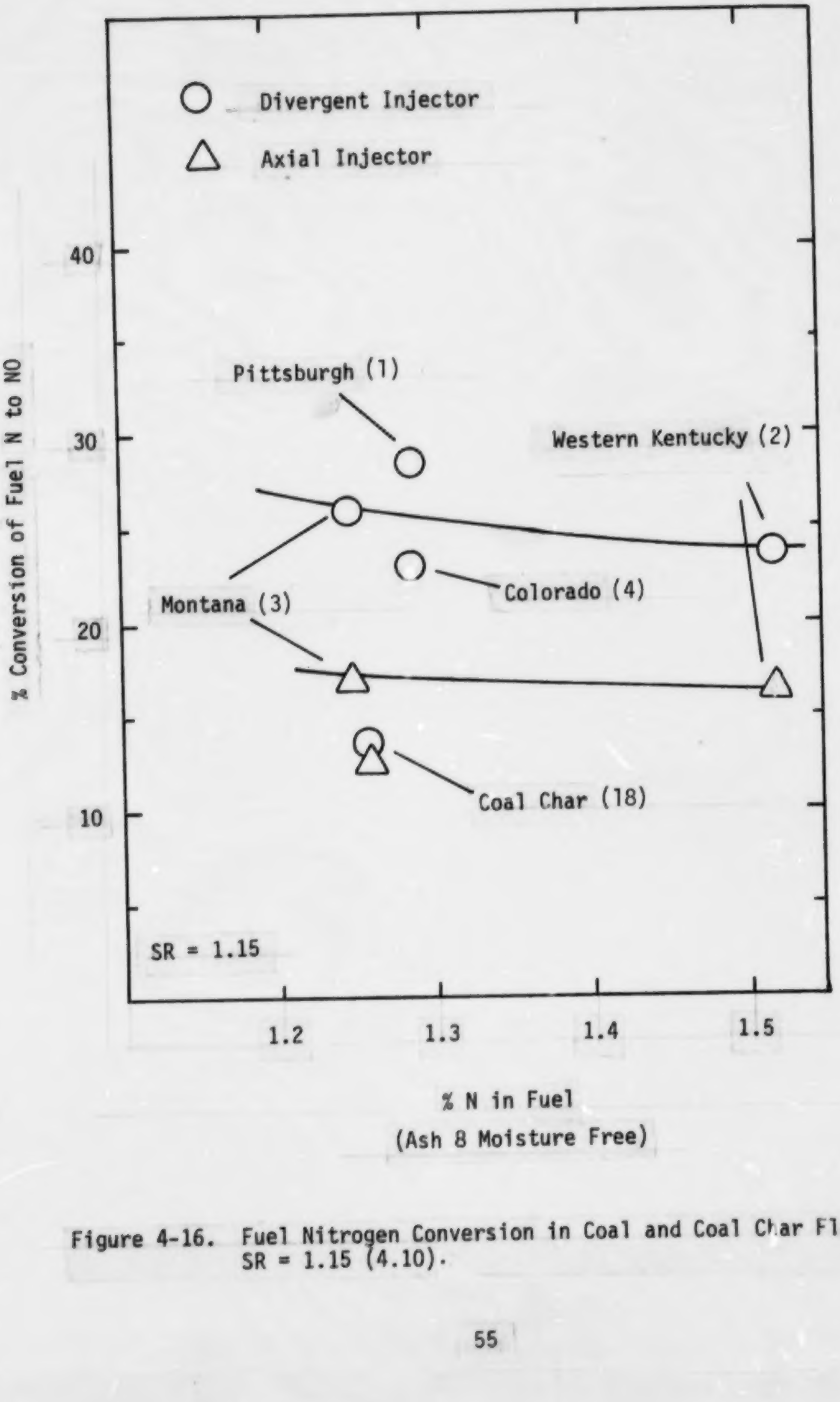


Figure 4-16. Fuel Nitrogen Conversion in Coal and Coal Char Flames SR = 1.15 (4.10).

nitrogen conversion to NO is discussed later in this report. The results reported by Pershing for these two coals do not support a hypothesis that fuel NO formation increases as coal O_2/N_2 ratio increases. It could be speculated that these results are due to differences in fuel sulfur level since it appears that there is no satisfactory explanation for the results presented in Figure 4-16.

The crucible results shown in Figure 4-12 indicate that for temperatures above $1400^{o}K$ there is very little difference in the ultimate char nitrogen content. With the exception of the MIT experiments, the data discussed earlier was obtained at temperatures and heating rates far below those encountered in flames. Pershing et al. used oxygen enriched atmospheres to study the effect of temperature on fuel NO formation. Results presented in Figure 4-17 show two surprising effects:

- fuel NO formation appears to exhibit two regimes, the extent of which appears to be fuel-dependent. Initially fuel NO appears to be temperature-independent, but as the temperature increases there is a sharp increase in fuel NO formation. As the temperature increases further, fuel NO formation once more remains constant;
- at high temperatures it appears that thermal NO production decreases.

The leveling off of both the fuel and thermal NO curves occurs only with oxygen-enriched atmospheres, and therefore, the results shown in Figure 4-17 may be attributable to something other than a temperature effect. Pershing(4.10) suggests that the increased O_2 partial pressure and the elevated temperatures somehow enhance the formation of N_2 from nitrogen specie. Song et al.(4.9) have reported that although increased temperature will increase the fraction of volatile nitrogen, the conversion of volatile nitrogen decreases with temperature. Char nitrogen conversion also appears to decrease with increasing temperature (see Figure 4-15). Thus, there may well be compensating effects which account for the results obtained by Pershing.

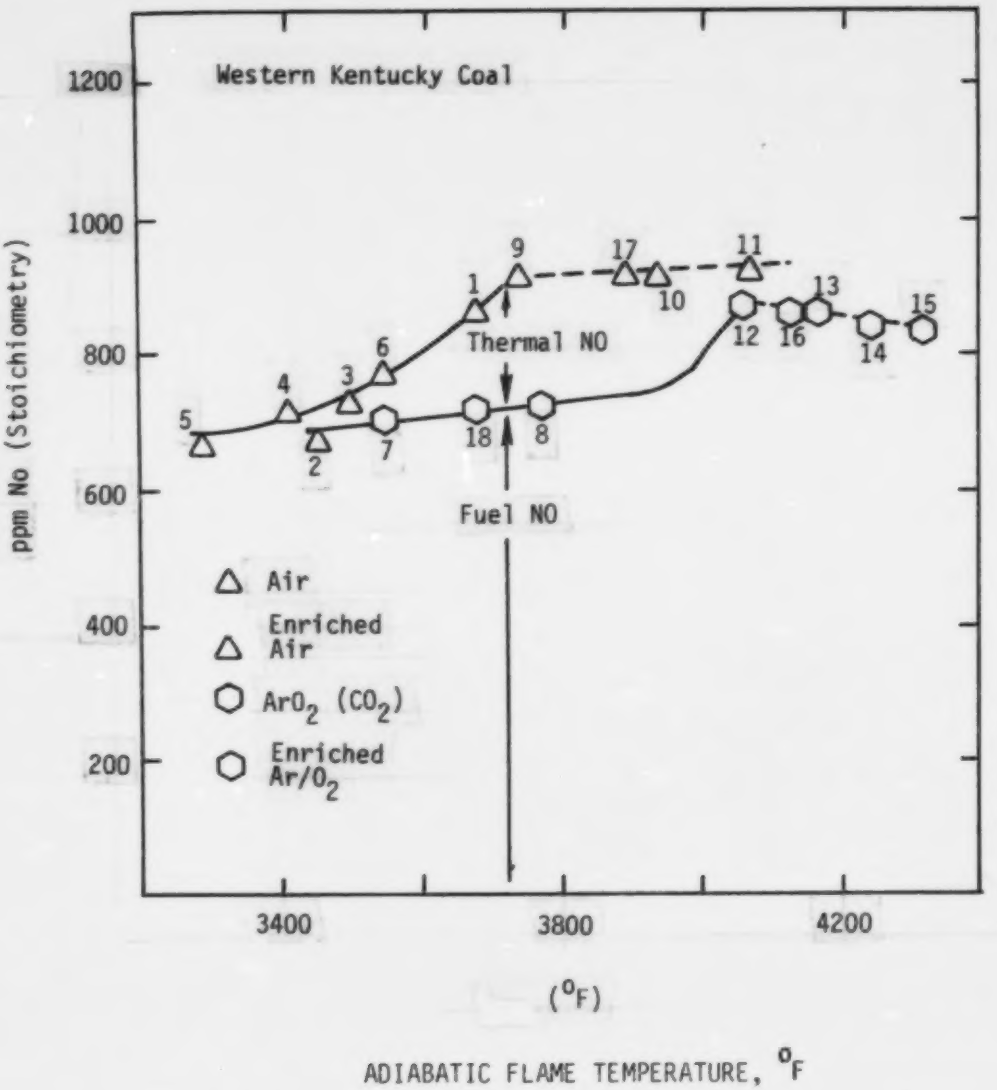


Figure 4-17. Effect of Temperature Increase by Oxygen Enrichment, Western Kentucky Coal, Divergent Injector, SR = 1.15.

Milne and Beachey(4.13) have reported gaseous species, particulate and temperature profiles for pulverized coal air flames produced with a Pittsburgh seam coal (No. 30). The coal particles were sized between 10 and 20 μm and the flames were stabilized unaugmented on a 6.3 cm diameter burner. Proximate analyses are presented for samples collected throughout the flame using ash as the normalizing standard. Seventy percent of the volatile content was lost before the primary reaction zone. HCN, NO and NO_2 were also observed upstream of the bright primary reaction zone in rich flames. Smoot and co-workers at Brigham Young University(4.14) have constructed a pulverized coal experimental test furnace to investigate the factors controlling pollutant formation in coal flames. The coal being used is a high volatile bituminous coal from Utah (No. 31).

Vogt and Laurendeau(4.23) have described some preliminary measurements of NO produced from premixed air/coal and air/char mixtures in an electrically heated furnace. Three fuels were used: COED char (34), Armco coke (35) and Armco coal (36) with a particle size such that everything passed through 140 mesh. The results are presented in Figure 4-18 as percent conversion to fuel NO of the fuel nitrogen. These workers assumed that thermal NO production was zero, presumably because furnace wall temperatures were maintained below 1100°C. Vogt concludes:

- For wall temperatures from 800 to 1100°C conversion rates of 10-25 percent are achieved.
- Fuel NO emissions are temperature-dependent at low temperatures.
- At some wall temperature there appears to be a large increase in fuel NO production and that above this temperature fuel nitrogen conversion increases with increasing excess air.
- Volatile NO emissions are significant at wall temperatures as low as 750°C.

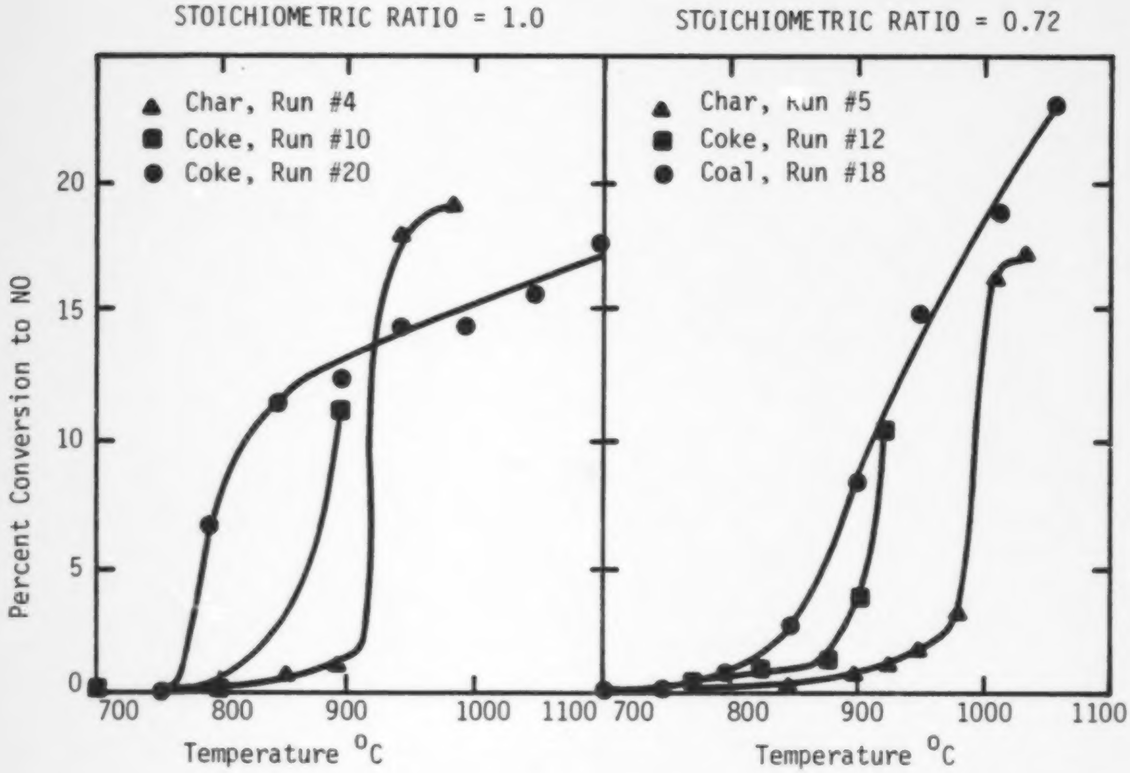


Figure 4-18. Comparison of NO Emissions from Char, Coke and Coal (Ref. 4.23).

The results presented in Figure 4-18 are of interest because they do show a fuel effect. However, the conclusions drawn by the experimenters are clearly open to question. Inlet air velocities (combustion air was cold) were low and the particles can be considered to be in free fall. No measurements other than fuel nitrogen conversion are reported which is calculated assuming all NO results from fuel nitrogen oxidation because of the low furnace temperatures. Under these conditions wall temperature is a poor indicator of particle temperature and the sudden increase in NO with wall temperature may be an ignition phenomena, whereas the low values are probably representative of fuel nitrogen pyrolysis. If ignition does occur, then the assumption of zero thermal NO is clearly fallacious, particularly under fuel-lean conditions. It is interesting to note that at higher temperatures the coal and the coke give very similar fuel "nitrogen conversions". It should be noted that the reported conversions assume all the nitrogen in the coal has reacted.

Development Programs

The objectives of most of the development programs reported on to date have not included a systematic investigation of the influence of coal composition on NO production. The work of Heap et al.(4.15) at the IFRF included tests with four fuels, three coals and a petroleum coke, and was mainly directed toward identification of design criteria for low NO_x coal burners. Coals 19 and 20 were tested under comparable conditions and coal 20 gave higher emissions than coal 19 under conditions designed to give rapid fuel/air mixing. The increased emissions could be expected because of the higher nitrogen content (1.8 percent c.f. 1.17 percent). However, this is a large change in fuel nitrogen content compared to a small change in emissions. The inert pyrolysis results of Axworthy (4.1) given in Table 4-1 show that coal 19 yielded a much higher percentage of HCN than any of the other bituminous coals. These results could be interpreted to suggest that the details of the coal nitrogen evolution rate were dissimilar for the two coals. Thus, the impact of the higher total nitrogen content for coal 20 on emissions is modified by the higher conversion of coal nitrogen to HCN for coal 19.

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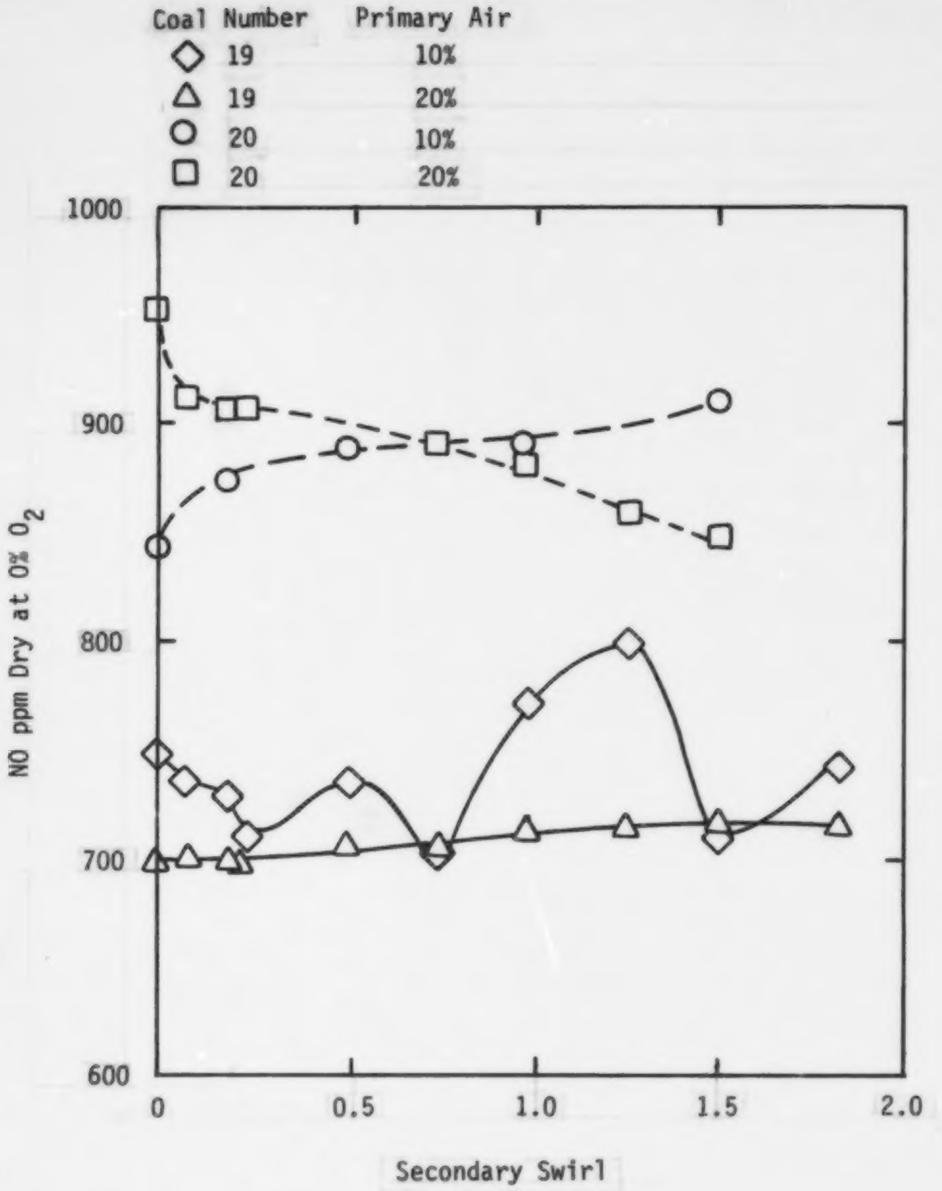

Figure 4-19. Emission Characteristics of Pulverized Coal Flames Produced (5% Excess Air, 300°C Preheat).

Armento(4.16) burned two coals (Nos. 4 and 32) in an experimental test tunnel with a scaled-down utility boiler burner. Coal nitrogen content was determined by the Kjeldahl method. Although the Colorado coal is shown to have a slightly higher nitrogen content, Armento claims that statistically the nitrogen levels were equal. Their oxygen levels are similar, but the Colorado coal has less than half the sulfur content of the Ohio coal. Table 4-3 summarizes the results obtained by Armento for the two coals and allows a comparison with natural gas. The effect of most variables was similar for both coals; however, the baseline emissions were different. NO emissions from the Colorado coal were 25 to 50 percent higher than those from the Ohio coal. Armento claims that the Colorado coal exhibited a different type of flame structure than the Ohio coal. Under normal or high excess air conditions the Colorado coal gave a clear flame, more like a natural gas flame. Only at low excess air did the flame become similar to the large luminous Ohio coal flame.

Flue gas recirculation results suggest that there was very little difference in the thermal NO produced by the two coals suggesting that the difference in emissions was due to differences in fuel nitrogen conversion. The difference in fuel nitrogen conversion could be associated with a variation in sulfur content or a variation in the volatility of the fuel nitrogen for the two coals. Both of these reasons are pure speculation at this time. It is interesting to note that the Colorado coal appears to have superior burning qualities.

Brown, Mason and Neubauer(4.17) chose three coals (Nos. 1, 2 and 3) with which to conduct development studies on staging parameters. Their rationale for selection was based mainly upon usage and not because they represented a variation in properties. This development program is being carried out in a combustor designed to simulate the aerodynamics of either a wall-fired or tangentially-fired boiler. The basic firebox is a 39-inch refractory lined heat exchanger. Movable heat exchanger units allow the variation of the combustion gas quench rate, the furnace residence time or the combustion volume. Staging ports are included in each of the heat exchange sections allowing the residence time in the first and second

Table 4-3. Summary of Results for Three Fuels (After Armento[4.16])

	Colorado Coal No. 4	Ohio Coal No. 32	Natural Gas
Excess Air			
Emission at 15% Excess Air	1100 ppm	700 ppm	300 ppm
Max. Emission (Excess Air)	1350 ppm (35%)	1000 ppm (35%)	350 ppm (20%)
Load			
20 - 60 K Btu/ft^3 hr	700-1150 ppm	400-800 ppm	No effect
Preheat			
300 - 700 ^{o}F			
15% Excess Air	925-1050 ppm	No effect	750-1000 ppm
30% Excess Air	1100-1350 ppm	750-1000 ppm	100-300 ppm
Flue Gas Recirculation			
Percentage Reduction	12%	5% (but at reduced rate)	85%
Staged Combustion			
Max. Reduction %	70%	60%	90%
Theoretical Air at Burner	55%	55%	50%

stages to be varied. The combustor is fired by five "IFRF" swirl burners or four corner-fired burners. This development program is continuing and this review includes the results reported to date.

F 4-20

Figure 4-20 compares the baseline emissions from the three coals tested by Brown et al. for two firing methods — wall- and corner-fired. Although there is some difference between emissions from the three coals, the Montana coal gives the highest emission; the differences are not considerable. Differences are more evident under staged conditions for the wall-fired condition suggesting that the decay of ΣXN compounds in the rich zone (which has a residence time on the order of seconds) may be different for the various coals (Figure 4-21). However, there were no differences when the firing rate was increased from 1.0 to 1.5 x 10^6 Btu/hr. As shown in Figure 4-16, Pershing(4.10) found that the Pittsburgh coal gave the highest fuel nitrogen conversion and would be expected to give the highest emissions. However, Pershing's data were not obtained at a constant firing rate which could invalidate the comparison. The variation in NO measured by Brown et al. can also be attributed to variations in sulfur level.

F 4-21

Field Test Data

Field test data are available(4.18) which illustrates the influence of operational parameters, boiler type and biased firing on the emission of NO_x from utility boilers. Dykema(4.19) has attempted to analyze this test data by classifying the seven coal types into four general coal groups. The coal properties are only introduced into the analysis on the basis of stoichiometry. Crawford's own analysis of the data is on the basis of Gross Load per Furnace Firing Wall which takes no account of the coal properties. On the evidence of these studies it could be concluded that fuel parameters do not have a strong influence on NO_x emissions from practical boilers. Any fuel effects are apparently masked by the strong dependence of emissions on mixing and furnace parameters. This dominant effect of firing mode is illustrated by the results presented in Figure 4-22.

F 4-22

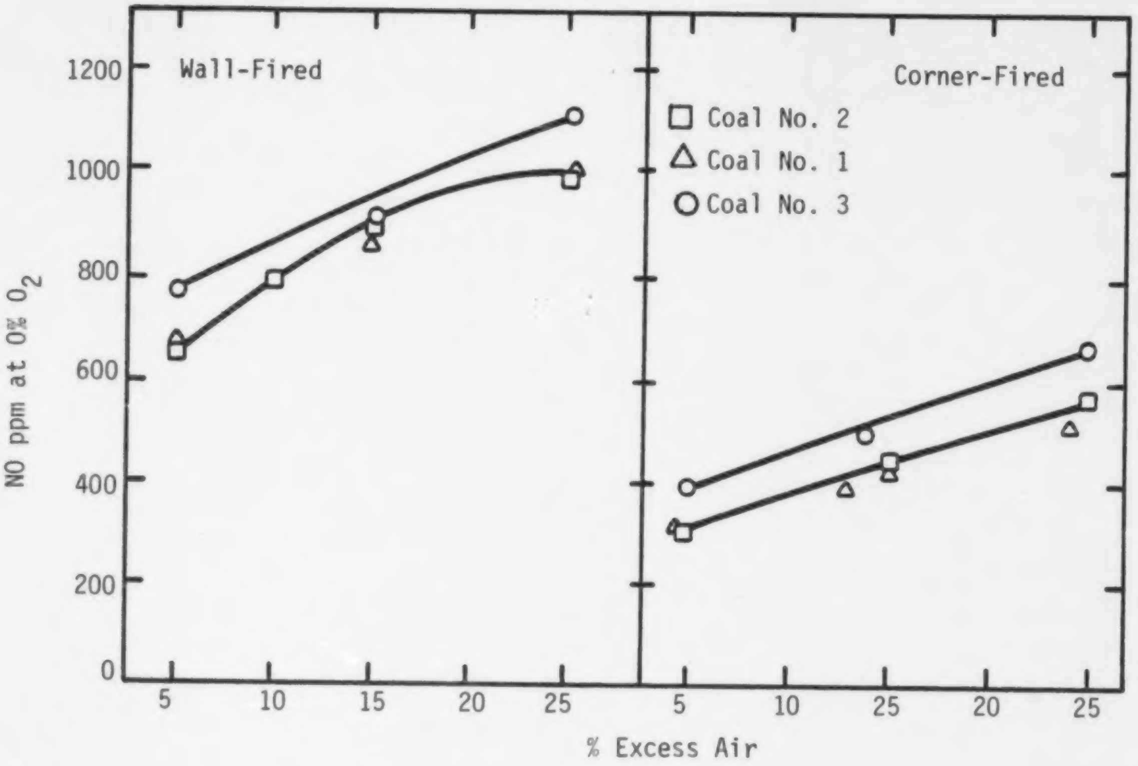

Figure 4-20. Effect of Coal Type of Baseline Emissions (After Ref. 4.17).

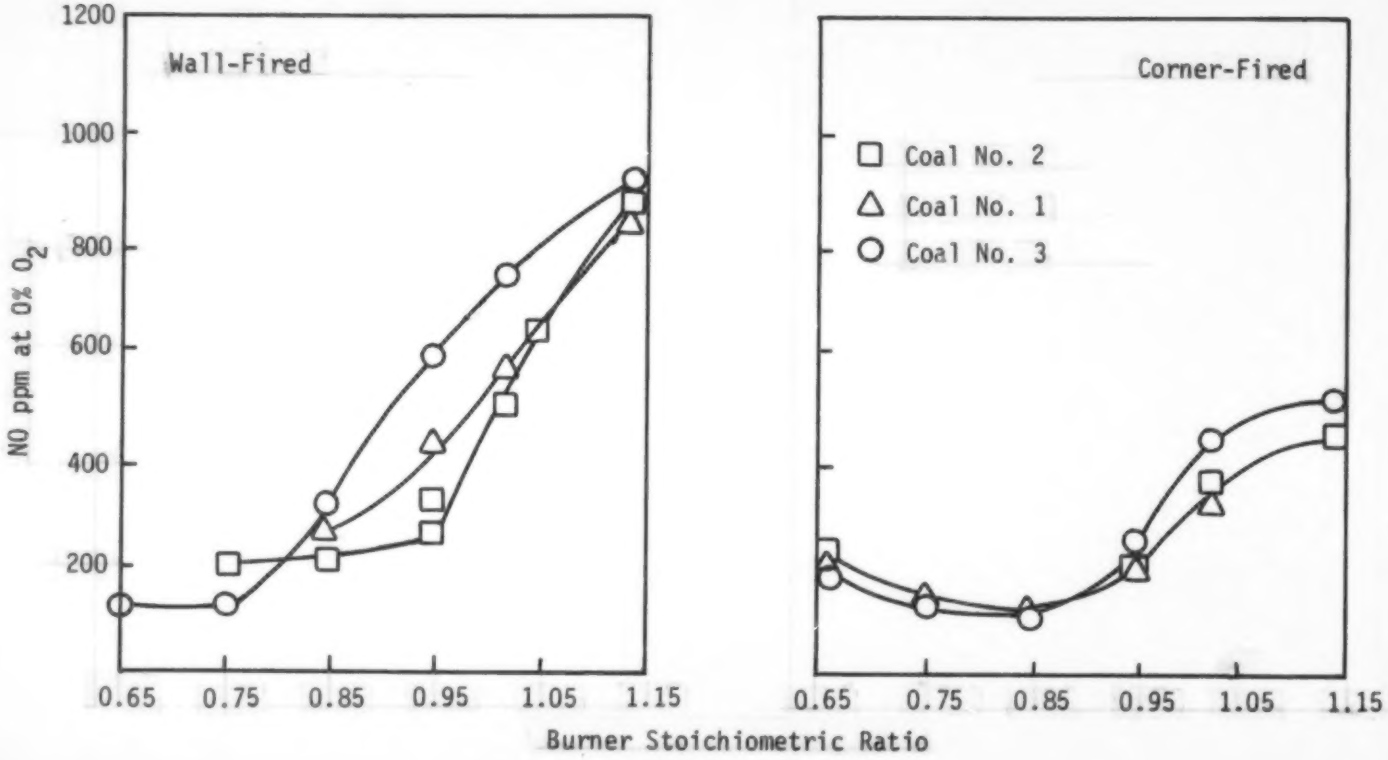

Figure 4-21. Effect of Coal Type on Staged Emissions (after 4.17)

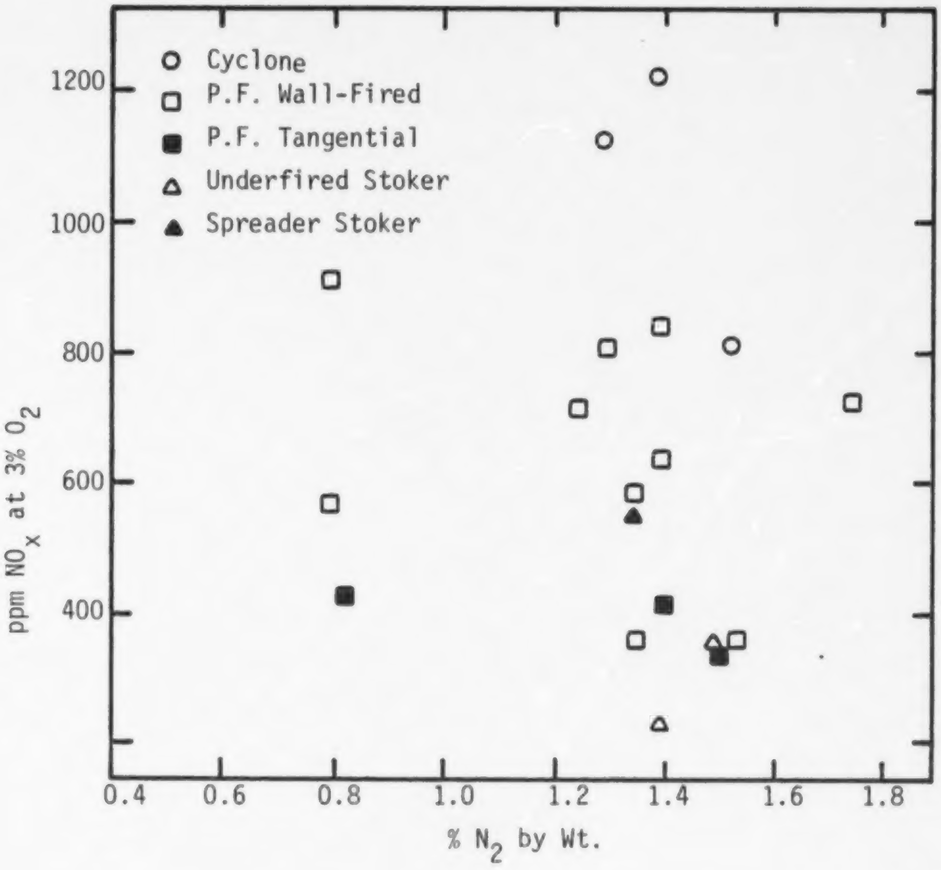

Figure 4-22. Correlation of Emissions from Field Tests as a Function of Fuel Nitrogen Content (after 4.18).

Habelt$^{(4.20)}$ has correlated the conversion of coal nitrogen to NO in tangential-fired boilers on the basis of coal nitrogen-to-oxygen ratios. This correlation was arrived at by estimating fuel NO production based upon the empirical model of Beuters et al.$^{(4.21)}$ which is itself open to criticism. Habelt justifies the correlation on the basis that coal oxygen represents a significant source of oxygen in the otherwise fuel-rich jet. For a high oxygen Western subbituminous coal, the coal oxygen can constitute up to a third of the total available oxygen in the mill air/pulverized coal stream. Habelt also considers that the coal oxygen is "in more intimate relation to the coal-bound nitrogen". Figure 4-23 compares Habelt's correlation with the data obtained by Pershing$^{(4.10)}$. The coals used by Pershing do not cover a wide oxygen-to-nitrogen ratio, but there is no obvious correlation nor agreement with Habelt.

Muzio et al.$^{(4.22)}$ measured NO_x emissions from pulverized coal-fired industrial boilers and report atypical emissions from a high oxygen coal (coal No. 33). These workers also link coal oxygen content with high fuel nitrogen conversion efficiencies. However, a coal with similar oxygen level burned on a spreader stoker did not give unusually high emissions.

4.1.2 Sulfur

The presence of sulfur in coal is one of the reasons for referring to coal as a dirty fuel since it results in the emission of sulfur oxides. Sulfur removal prior to combustion is one major factor in the development of coal conversion technology since it will be less costly to remove sulfur as a reduced specie rather than to scrub sulfur dioxide from the flue gases. The fate of coal sulfur is of interest to this project for two reasons:

1. Sulfur Retention. The axiom "sulfur in equals sulfur out" does not apply to coal; the inorganic coal matter can contain compounds which form stable sulfates at high temperatures and sulfur is retained in the ash.

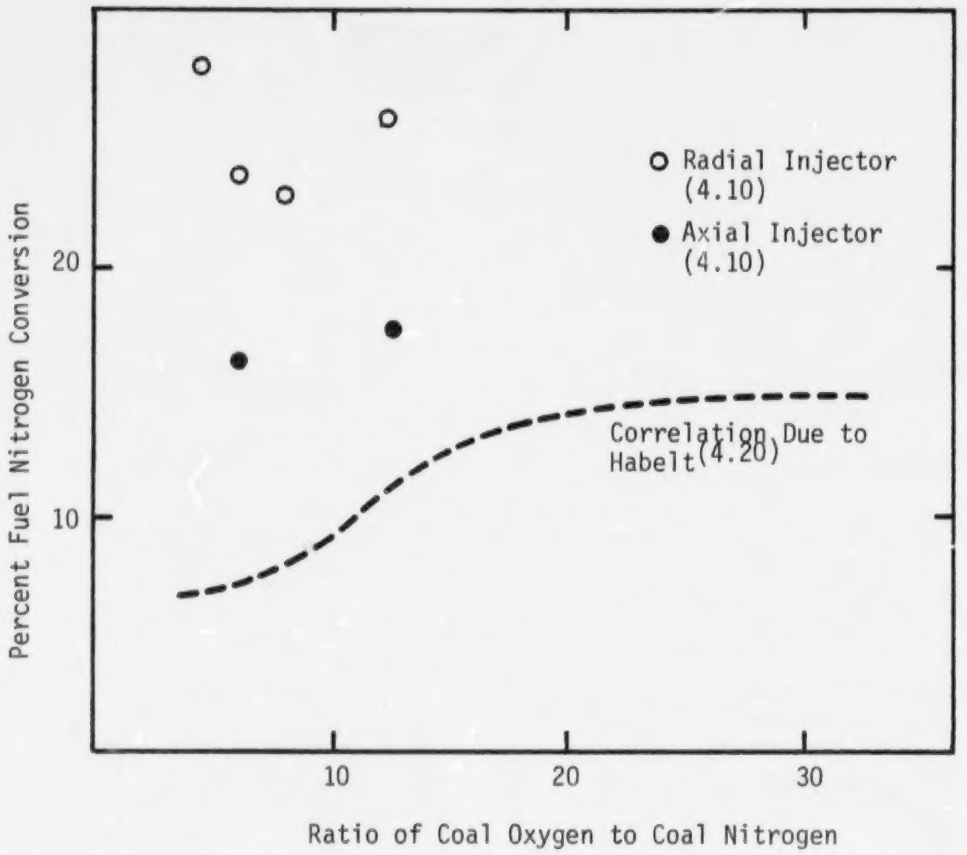

Figure 4-23. Comparison of Pershing's Data with the Correlation of Habelt (4.20).

2. SO_x/NO_x Interaction. Sternling and Wendt(4.24) considered that because sulfur dioxide catalyzed the recombination of oxygen atoms, the presence of sulfur would suppress thermal NO formation. However, recent experimental evidence appears to suggest that gas phase reactions under fuel-rich conditions between SX and NS compounds affect the balance of nitrogenous specie (NO, NH_3 and HCN). This interaction could well affect the residence time necessary in a rich zone to minimize NO production.

Traditionally, sulfur in coal has been divided into two classes: 1) inorganic sulfur, and 2) organic sulfur. Two classes of inorganic sulfur are considered, disulfides and sulfates. A working definition of the different sulfur forms is(4.25):

- Sulfate sulfur is the sulfur equivalent of the amount of sulfate ion which dissolves in dilute hydrochloric acid in 30 minutes.
- Pyritic sulfur is the sulfur equivalent of the ion which dissolves in boiling twice normal HNO_3 in 30 minutes.
- The organic sulfur is the difference between the total sulfur and the sum of the sulfate and pyritic sulfur.

The total sulfur in coal varies with source, the organic sulfur is usually one-half to one-third of the total sulfur and the sulfate rarely exceeds 0.1 percent of the total weight. Thus, most of the sulfur is in the form of iron disulfide FeS_2.

Iron disulfide appears in two crystalline forms(4.26), the pyrite (cubic) and the mareasite (rhombic). Since the major portion of the FeS_2 is pyritic, the name pyrite is quite often used to designate all FeS_2. The organic sulfur appears to be spread throughout the organic matrix whereas FeS_2 appears in the form of loose crystals which form vane-like structures in the organic coal seam. Since the density of organic matrix is in the range of 1.2 - 1.5 gm/cm^3 and that of pyrite is 5.0 gm/cm^3, physical methods can be used to separate the pyrite from the organic material. The **dominant** form of organic sulfur in coal is thought to be sulfur, and Solomon(4.4) indicates that about 60 percent of the organic sulfur resides in such heterocyclic rings. Mercaptins, sulfides and disulfides are other forms of organic sulfur.

There has been a considerable body of knowledge generated on the evolution of sulfur during the devolatilization and hydrodesulfurization of coal(4.27,-28,-29,-30). The process is complicated because of the existence of competing reaction processes among several forms of sulfur, i.e., sulfate, iron sulfides and several organic sulfur forms. Solomon(4.4) summarized the reactions which are considered to affect the distribution of sulfur in the devolatilization products of coal:

1. Pyrite (FeS_2) decomposes at low temperatures, 400°C, to form ferrous sulfide FeS. Sulfur is released as H_2S or more complex organic compounds.
2. At 900°C FeS decomposes to form Fe releasing sulfur and sulfur compounds.
3. Thermal decomposition of organic sulfur occurs in stages, some of which is released at low temperatures, 400°C or 500°C, and some is incorporated into the organic structure of the char.

Solomon(4.4) has reported concentrations of sulfur in tar char and gas as a result of devolatilization under vacuum in the apparatus described in the previous section which agree with the above generalizations. Specific observations from this work include:

- at low temperatures the sulfur content of the tar approaches the organic sulfur level in the coal. At high temperatures there is an increase in the tar products and the sulfur evolved from the pyrite;
- devolatilization of coals with a low pyrite content tends to decrease the organic sulfur level in the char.

In coals with a high pyrite content, the organic sulfur in the char increases with increasing temperature as sulfur evolved from the pyrite combines with the organic structure;

- organic sulfur compounds are more volatile than carbon and nitrogen, but less volatile than oxygen and hydrogen; indicating that, although some sulfur exists in weakly bound sites such as mercaptans or sulfides, most is in lightly bound structures such as thiophenes; and
- results for all coals show high sulfur levels in the gas, mainly in the form of hydrogen sulfide.

Tests(4.31) on power plants burning Western coals have indicated that from 10 to 40 percent of the total sulfur ends up in the fly ash. In fluidized bed combustion where the temperature is lower, sulfur oxide control is achieved by in situ contacting with limestone or dolomite. Coals with high calcium, magnesium and sodium contents normally have good sulfur retension characteristics. As sulfate stability decreases with increasing temperature, low NO_x conditions might promote sulfur capture.

4.1.3 Mineral Matter

The ash forming constituents of coal can be divided into two categories(4.32):

1. Inherent mineral matter derived from the original plant substance.
2. Extraneous mineral matter that was mixed with the plant substance as the coal was formed or during mining operations.

The former category rarely exceeds 2 percent of the coal mass. Coal mineral matter composition is important because of influence on fouling, corrosion, and the emission of trace species. Fly ash size distribution can also affect precipitator efficiency. The mineral matter in coal undergoes a number of transitions as the coal is heated(4.33). At temperatures below $500^{0}K$ changes in the mineral form occurs together with dehydration. Carbonates and sulfates decompose and alkali salts such as chlorides are volatilized at temperatures higher than $1900^{\circ}K$ due, in a large part, to the reduction of SiO_2 with carbon to form SiO which is more volatile than SiO_2. The influence of combustion on the fate of coal mineral matter is a topic which will receive considerable attention as the project progresses, and future updates of the program plan definition will include more detail on this subject.

Sarofim, Howard and Padia(4.34) studied the physical transformation of the mineral matter in pulverized coal in the MIT rapid heating furnaces discussed in a previous section. The coals studies were Nos. 6 and 7 and they found that three major mechanisms affected the particle size distribution of the fly ash produced during combustion:

1. Ash particles agglomerate as the carbon matrix is consumed.
2. The larger particles and the size distribution is influenced by the formation of censopheres due to gas evolution during heating of the minerals.
3. Vaporization and recondensation increase the percentage of submicron particles as the temperature increases. Silica was the major component vaporized in amounts that reached 4 percent of the total ash weight at $1800^{\circ}K$.

4.2 Fuels Selection Criteria for First Year's Effort

The primary thrust of the first year's experimental program will be to determine to what extent coal properties influence NO_x production in coal flames in general, and the performance of the low NO_x distributed mixing burner (DMB) in particular. The experimental program can be divided into three groups.

- all the fuels selected will be tested under well-controlled conditions in the small-scale (approximately 100,000 Btu/hr input) refractory furnace capable of burning the fuel with an oxidant which does not contain molecular nitrogen. These small-scale experiments will be used to assess the requirements of low NO_x burners for various fuels.

- a maximum of five fuels will be selected for testing at a firing rate approximately 10 x 10^6 Btu/hr under low NO_x conditions.
- some of these same fuels will also be tested at a firing rate of approximately 50 to 120 MBtu/hr in single burners as well as multiple burner arrays.

Since the program is concerned with the control of NO_x emissions from coal-fired boilers it is useful to summarize briefly those factors which influence NO_x production in coal flames and the steps that can be taken to modify the combustion process in order to minimize the final emission level. Coal contains chemically-bound nitrogen and NO_x can be produced during combustion, either by the oxidation of this coal-bound nitrogen (fuel NO) or by the fixation of molecular nitrogen (thermal NO). It is generally recognized that in uncontrolled pulverized coal fired boilers approximately three-quarters of the total NO_x emission is fuel NO. Available information on the fate of coal nitrogen was reviewed in the previous section of this report where it was shown that during the heating process the total nitrogen in the coal is divided into two streams; some is driven off as a volatile compound and some nitrogen is left in the char. The rate of volatile nitrogen evolution appears to be dependent upon the particle final temperature and perhaps upon the heating rate. These volatile nitrogen compounds will react producing either NO or N_2, depending upon the availability of oxygen. Combustion modification to control NO formation involves the production of a fuel-rich primary zone to maximize the conversion of volatile fuel nitrogen compounds to N_2. The mechanism whereby char nitrogen is converted to NO is not well-understood; however, it is generally recognized that char nitrogen conversion accounts for the minor part of fuel NO production in uncontrolled coal flames. There is no evidence to suggest that this also applies under low NO_x

conditions. As the name implies, thermal NO production is strongly dependent upon temperature and its formation rate can be controlled by minimizing the temperatures within the combustion zone. This can be achieved either by dilution of the reactants with cool inert gases, or by staged combustion with interstage heat removal. Consequently, the coal properties which will influence NO production in pulverized coal flames will be associated with the total nitrogen content of the coal, the nitrogen evolution rate as a function of temperature, and those coal properties which influence combustion rate (i.e., particle heating rate).

In addition to the provision for information on the coals to be tested at larger scales, it is hoped that the small-scale tests will also provide a correlation of some form linking NO production as a function of input parameters (overall excess air, firing rate, primary zone stoichiometry and residence time, fuel injection characteristics, particle size, etc.) with coal properties. Therefore, it is essential that the fuels selected have a sufficiently broad range of properties to allow such a correlation to be made, if at all possible. To ensure the relevance of the program as a whole, it is necessary for the most part that the fuels tested be representative of those used by the utility boiler industry; however, some coals will be selected because they will help to provide better understanding of the fate of trace specie during the combustion of pulverized coal. Coal properties, information concerning the characteristics of the coal under combustion conditions, and its availability for both small- and large-scale testing are the criteria that have been used in the fuel selection process. The previous section of this report reviewed the information available on the performance of many American coals and this aspect will not be discussed further. The availability of the fuels has not been researched to date. It has been assumed that since all the coals are reasonably well-characterized they can be obtained from the same mine, or coals of very similar properties can be selected as backups.

The coal properties which have been considered are:

- Coal Rank. The methods of classiying coals and the ASTM ranking procedure provides a basis for grouping coals by the degree of coalification. The age of coals increases with rank, thus lignites are the youngest coals and anthracites are representative of the oldest coals. Coal rank is indicative of moisture content, volatile content (material driven off when the coal is heated in the absence of air under set conditions), fixed carbon (the residue after the loss of volatile matter), heating value and agglomerating and weathering properties. Medium volatile, low volatile, and anthracite coals are of no importance with regard to practical application of low NO_x burners. However, some coals which fall into these ranks will be selected to provide a broad spectrum of properties. Coal rank can be considered to be representative of those properties which will influence the combustion process as a whole.

- Nitrogen Content. Since the oxidation of coal nitrogen is an important source of NO during coal combustion, the fuels selected for testing should have as wide a range of coal nitrogen content as possible. In addition to the overall range of nitrogen content, it is also necessary that a range of nitrogen contents within each rank be tested in an attempt to differentiate the influence of nitrogen content and combustion properties on NO production.

- Sulfur Content and Sulfur Speciation. It is known that sulfur species influence the interconversion of nitrogenous species in rich combustion products. Therefore, it is reasonable to believe that the sulfur content of a fuel could affect fuel nitrogen oxidation, and fuels should be selected within a particular rank with a variety of sulfur levels. Since it can be assumed that organic sulfur is evolved with the volatile nitrogen fragments, the division of the coal sulfur between organic and pyritic may also play a part in the fuel nitrogen conversion process. Consequently, an attempt will be made to test fuels with different organic-to-pyritic sulfur ratios.

- Oxygen-to-Nitrogen Ratio. As discussed previously, it has been suggested that the coal oxygen-to-nitrogen ratio influences the formation of fuel NO. Therefore, coals should be selected with a wide range of this parameter for given ranks.
- Ash Properties. Coal ash is an important practical parameter since it must be paid for, shipped, conveyed, pulverized, heated, collected, and disposed of. Ash properties influence slagging, fouling, and deposition at low temperatures. In the first year's test program a systematic variation in ash properties within a given rank will not be of primary concern. However, after establishing a preliminary correlation the effect of ash properties (softening point, viscosity, sulfur retention characteristics) will be of primary concern for the following year.

Coal is found in abundance in over 30 states in the U.S. Although no deliberate attempt has been made to cover as many states as possible, selection of a wide variety of coals will mean that fuels are tested from the major coal reserves. The system used by Spackman et al.(4.39) to classify the major coal provinces, regions and fields has been adopted in this report. This classification is as follows:

1. Eastern Province
   a. Appalachian Region - Pennsylvania, Ohio, Maryland, Virginia West Virginia, Eastern Kentucky, Eastern Tennessee, Georgia, Northern Alabama
   b. Anthracite Region - Pennsylvania
   c. Atlantic Coast Region - Virginia, North Carolina
2. Interior Province
   a. Eastern Region - Illinois, Indiana, Western Kentucky
   b. Western Region - Iowa, Missouri, Kansas, Nebraska, Oklahoma, Western Arizona

   c. Southwestern Region - Northern Texas
   d. Northern Region - Michigan

3. Northern Great Plains Province
   a. Fort Union Region - North Dakota, South Dakota, Eastern Montana, Eastern Wyoming
   b. North-Central Region - Montana
   c. Denver Region - Northwestern Colorado
   d. Raton Mountain Region - South-Central Colorado, Northeastern New Mexico
4. Rocky Mountain Province
   a. Bighorn Basin Region - Northern Wyoming, Southern Montana
   b. Green River Region - Southwestern Wyoming, Northwestern Colorado
   c. Uinta Region - Western Colorado, Eastern Utah
   d. Wind River Basin Region - Central Wyoming
   e. San Juan River Region - Southwestern Colorado, Northwestern New Mexico, Arizona
   f. Hams Fork Region - Western Wyoming
   g. Hanna Field - Southeastern Wyoming
   h. Southwestern Utah Region - Utah
5. Pacific Province
6. Gulf Province - Southeastern Texas, Southern Alabama, Louisiana, Southeastern Alaska, Mississippi
7. Alaskan Province

4.2.1 General Fuel Selection

Two sources were used as the basis for the selection of the fuels to be tested in the first year's effort. Appendix A lists those coals used by various investigators in laboratory, development and field test programs. Appendix B lists coals selected from the Penn State-ERDA Sample Bank(4.39) which were chosen to expand the ranges of fuels available in the various ranks. In Figures 4-24 through 4-28 symbols denoted

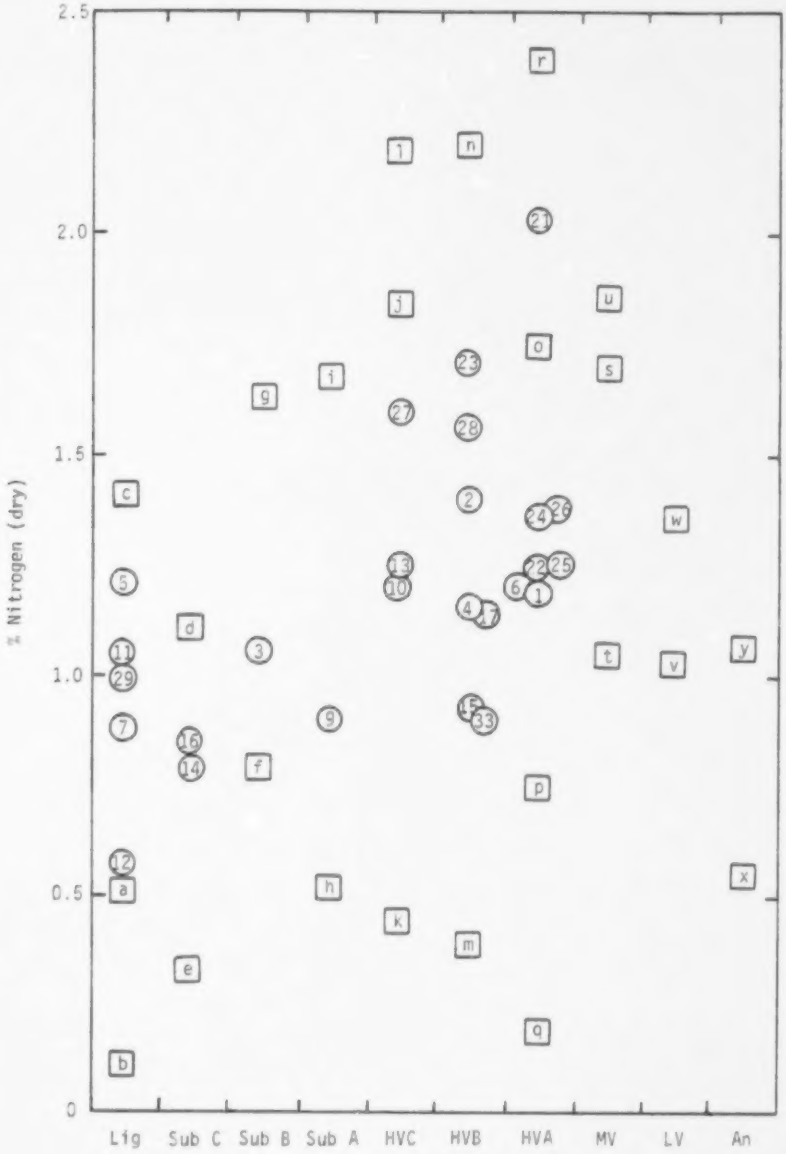

Figure 4-24. Coal Nitrogen Content as a Function of Coal Rank.

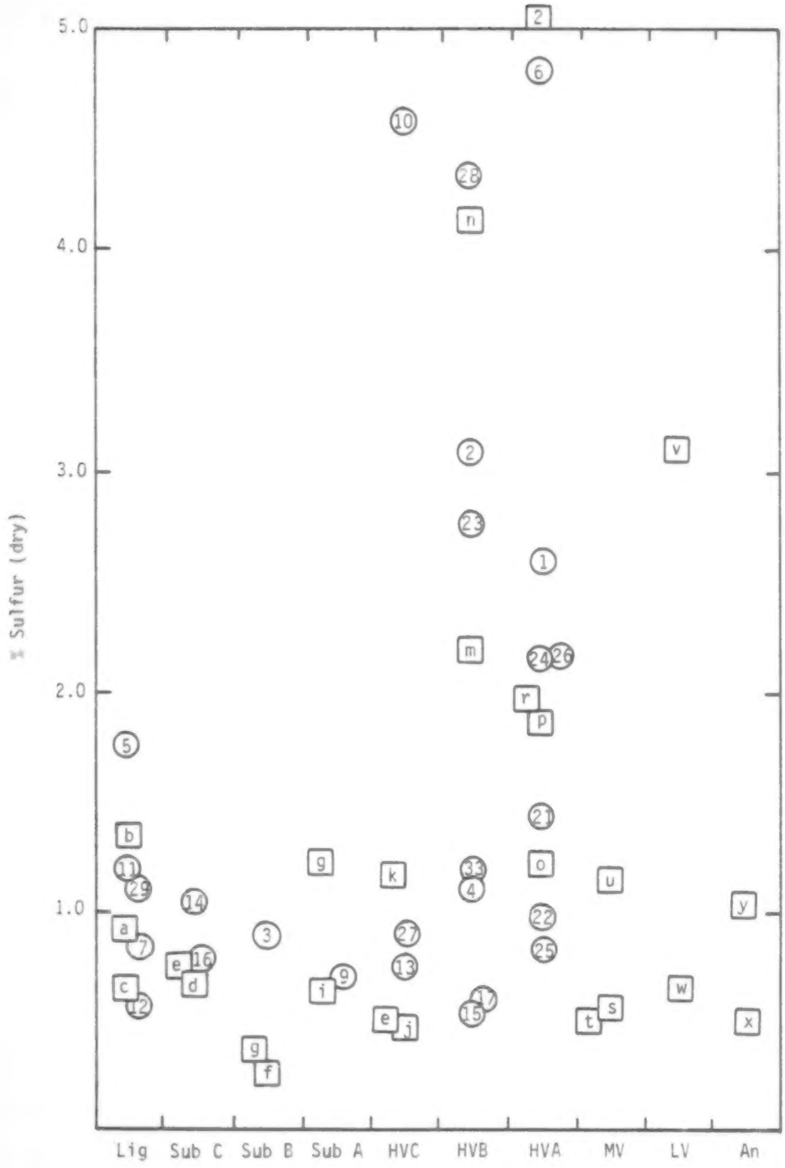

Figure 4-25. Coal S Content as a Function of Coal Rank.

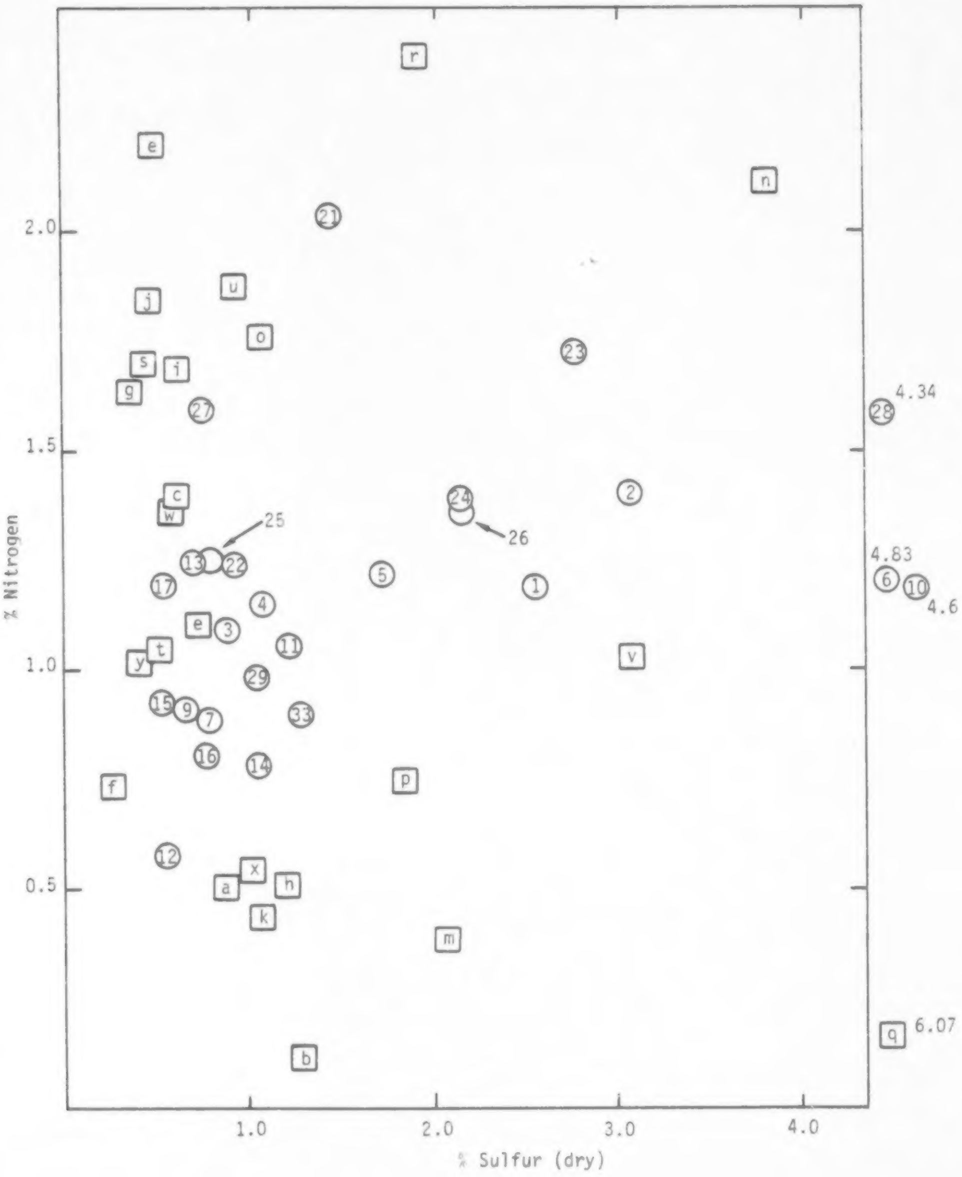

Figure 4-26. Coal Nitrogen versus Coal Sulfur.

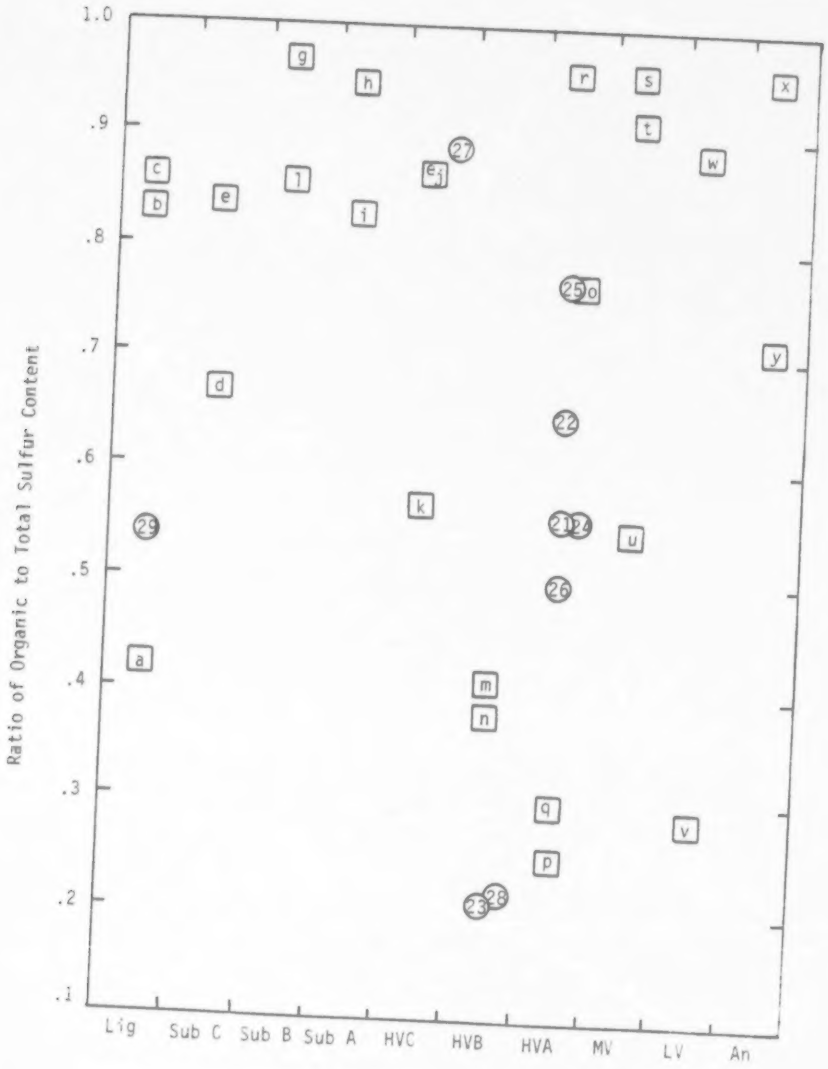

Figure 4-27. Ratio of Organic to Total Sulfur Content as a Function of Coal Rank.

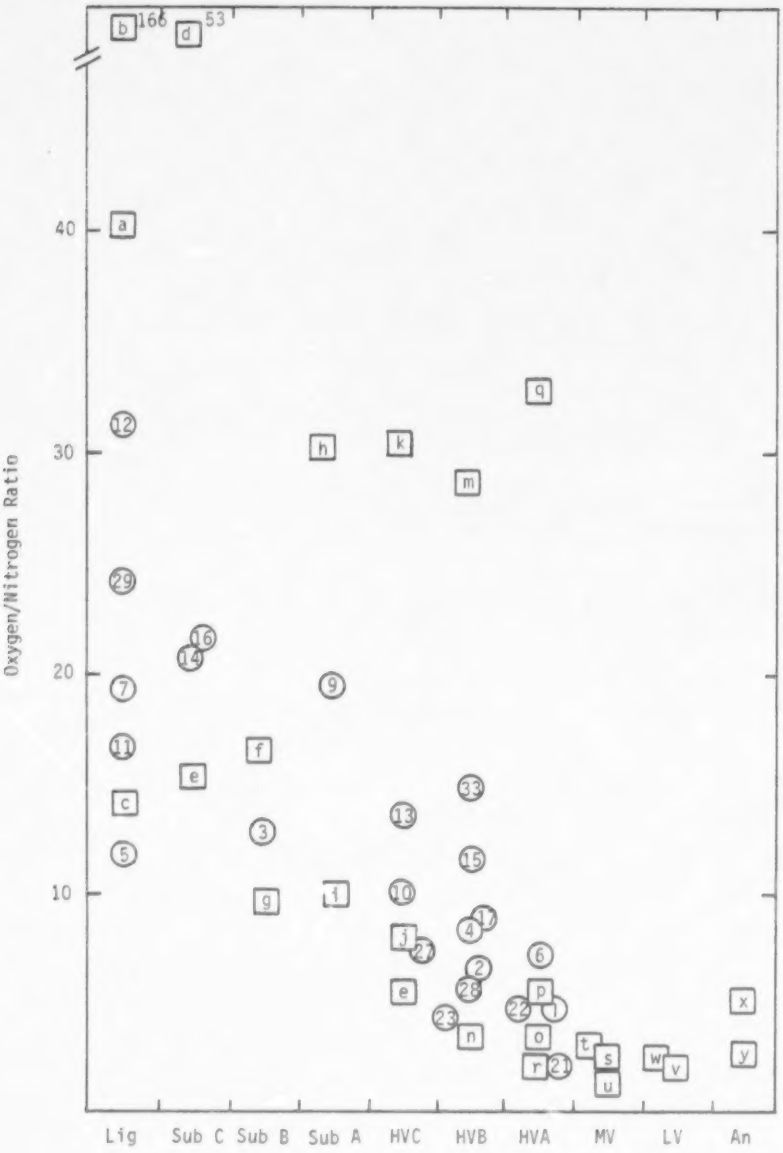

Figure 4-28. Oxygen Ratio as a Function of Coal Rank.

by a numeral in a circle refer to coals listed in Appendix A, symbols with a letter refer to Appendix B. Figure 4-24 compares the total set of coals on the basis of rank and weight percentage nitrogen in the dry coal. Figure 4-25 shows the same set, but in this instance differentiated by weight percent of sulfur dry. Figure 4-26 shows a cross-plot of coal nitrogen versus coal sulfur, and it can be seen that most of the coals have a sulfur content below 1.5 percent. This sulfur content is divided between the organic and the total sulfur level over a very wide range, as can be seen by the plot shown in Figure 4-27. Only a small fraction of the coals listed in Appendix A are shown in Figure 4-27 since information on the organic and pyritic sulfur content is not available. Coal oxygen-to-nitrogen ratios generally vary from greater than 30 to less than 2 and as shown in Figure 4-28 there is a relatively wide spread in the total set across various ranks. Table 4-4 lists the general coals selected for testing and the rationale for their choice is given below.

T 4-4

Anthracite Low Volatile and Medium Volatile Coals

The coals in those groups have no practical significance for power generation, however, it will be informative to test low volatile fuels to provide some information on the influence of combustion characteristics on fuel NO production. Coals Y, V and T have been selected because they all have similar nitrogen contents, and thus provide a check on the effect of volatility even though coal V has a higher sulfur content. These coals were chosen rather than coals S and X which are being used by Pohl(4.40) in a fundamental study at Sandia because of their consistent nitrogen content. Should coal Y not be available, then it will be replaced by coal X. Coal S will be obtained because this represents a high nitrogen medium volatile fuel.

High Volatile Coals

Five coals have been selected to cover Class A high volatile coals. They have been chosen primarily because they represent a wide range of nitrogen contents. Coal R from Virginia has a high nitrogen content (2.38 percent) and an intermediate sulfur content (1.96 percent). However, the organic sulfur content represents 96 percent of the total.

Table 4-4. Initial Coals Selected for Testing

RANK	IDENTIF.	NITROGEN	SULFUR	O_2/N_2	ASH	PROVINCE	REGION	REMARKS
Anthracite	Y	1.05	0.52	5.2	9.16	Eastern	Anthracite	Similar nitrogen content to T and V
Low Volatile	V	1.03	3.10	2	10.6	Eastern	Appalachian	
Medium Volatile	T	1.05	0.52	3.05	6.4	Eastern	Appalachian	
	S	1.7	0.58	2.8	2.42	Eastern	Appalachian	High nitrogen content
High Volatile A	6	1.2	4.83		12.5			Used by Sarofim and Pohl, high sulfur
	21	2.03	1.46		5.09	Eastern	Appalachian	Used by Soloman
	P	0.75	1.87	5.6	10	Eastern	Appalachian	
	Q	0.16	6.07	32.7	13.13	Interior	Western	Low nitrogen, high sulfur
	R	2.83	1.96	2	5.9	Eastern	Appalachian	High nitrogen, low sulfur
B	2	1.4	0.9	6.6	12.46			Used extensively by various investigators
	15	0.93	0.53	11.6				Field test
	17	1.2	0.6	8.5	7.4			Coal used on Contract 68-02-1488
	33	0.9	1.2	14.8	11.3			Field test gave high NO_x
	M	0.39	2.21	28.6	11.3	Interior	Eastern	Low nitrogen
	N	2.2	4.15	3.3	8.9	Interior	Eastern	High nitrogen
C	10	1.2	4.6	10	9.4			
	13	1.27	0.75	13.6	22			Exxon tested at Four Corners
	27	1.6	0.9	7.8	3.05			
Subbituminous A	9	0.9	0.7	19.4	7.9			Investigated by Blair
B	G	1.63	0.39	9.6	5.4	Northern Great Plains	Denver	
C	14	0.79	1.05	8.3				
Lignites	B	0.11	1.32	166	13.51	Northern Great Plains	Fort Union	Low nitrogen
	12	0.57	0.57	31.7	6.6			CE correlation
	7	0.88	0.84	19.7	21.68			Pohl and Sarofim, similar to Soloman
	5	1.21	1.75	11.8	17.6	Texas		Shell coal
	C	1.4	0.65	14	9.7	Northern Great Plains	Fort Union	

Coals 21 and 6 represent two high volatile coals characterized by other experimentalists. Solomon used coal 21 which is also from Virginia. It should be noted, however, that Solomon quotes a nitrogen content of 1.53 on a dry mineral matter-free basis which is considerably lower than that given in the Penn State coal data base. Coal Q has an extremely low nitrogen content. This is a Western coal from Vernon County, Missouri. It has a high sulfur (greater than 6 percent), 70 percent of which is pyritic. Examination of Figures 4-24 and 4-25 shows that the coals selected cover almost the entire range of nitrogen and sulfur content.

An attempt will be made to secure six coals in the high volatile Class B range. One of these, coal 17, is currently being used on Contract 68-02-1488. Coals M and N represent the low and the high range for nitrogen content. Coal 2 is the Western Kentucky coal used by investigators at Aerotherm, University of Arizona, and MIT and represents a coal used by a large number of investigators and the information could well be useful in defining the various experiments. Coals 17 and 33 represent coals used on field tests and are, therefore, ideal candidates to fire at scale to give some comparison between SWS and LWS testing and actual utility boilers. Coal 33 is a high oxygen coal that gave very high NO_x levels when tested by KVB in an industrial boiler. Again, the coals chosen represent the complete range of both nitrogen and sulfur content. An alternative choice in this class would be coal 28, since this was one of the coals tested by Solomon and it shows a different nitrogen evolution rate than coal 21.

Three coals have been selected to represent the high volatile Class C rank. Coal 10 was tested by David Blair at Exxon. Coal 13 is a coal used at a utility plant at Four Corners which was field tested by Exxon, and Coal 27 was one of the coals characterized by Solomon.

Subbituminous Coals

Coals 9, G and 14 have been selected to represent the subbituminous A, B and C groups respectively. Coals 9 and 14 have medium nitrogen levels and Coal G is a high nitrogen, low sulfur subbituminous coal. Coal 9 was one of the coals investigated by Blair at Exxon. Coal 14 was fired in a utility boiler and field tested as part of the NO_x EPA program. Baseline NO_x levels at 3.8 percent excess oxygen on the order of 520 ppm (corrected to 0 percent oxygen) were measured with this coal. This value was reduced to 389 ppm with overfire air operation.

Lignites

Five lignites have been selected covering a nitrogen content of 0.11 to 1.4 percent which corresponds to an oxygen/nitrogen ratio from 166 to 14, thus providing the opportunity to investigate the effect of oxygen/nitrogen ratio on fuel NO production. Coal 7 was chosen because it is similar to the coal investigated by Solomon and there is a large amount of data on this coal from EPA-sponsored studies at MIT.

4.2.2 Final Fuels Selected and Purchased

Although a number of coals were specified as being desirable for this study, until inquiries could be made it was not known whether they would be available for this program. For the coals that were not available, alternate coals having similar properties were selected. In addition, since the initial experimental effort is directed toward fuels screening at the 100,000 Btu/hr firing level only small quantities (~2-4 drums) were sought. Then from the results of the screening studies as well as the representativesness and data availability a choice will be made of which of the coals will be tested at the larger scales. The coals that have been acquired in the first year were obtained by:

1. Directly contacting coal companies for a specific coal,
2. directly contacting coal companies in a specific area,
3. directly contacting power companies that utilize the coal,
4. coals available on site.

A total of 24 coals were obtained in addition to the four coals already on-site for testing and represent almost the complete range of the initial coals selected for testing. Table 4-5 provides a list of the sources of the 33 coals that have been ordered under this contract, the quantity of

Table 4-5. Fuels Received

Coal No.	Source	Quantity Received (lbs)	Reference Appendix A and B
1	Long Construction, Colstrip, MT Two barrels Rosebud Seam	691	14
2	Western Coal Co., Farmington, NM One barrel Fruitland Formation - San Juan Mine	320	13
3	Arizona Public Service Co., Fruitland, NM Two barrels Utah International	500	13
4	Knife River Coal Mining Co. (KRMCO), Scranton, ND Three barrels	510	C
5	Kemmerer Coal, Kemmerer, Wyoming One barrel - 1/2 full Wyodak Coal Mine = Elkol Coal - Frontier, WY	80	9
6	Knife River Coal Mining Co., Beulah, ND Three barrels	750	12
7	Somerset, Colorado One barrel Bear Mine	400	4
8	Commercial Testing and Engr., 30 m E of Hardin, MT Two barrels	778	7

Table 4-5. Fuels Received (Continued)

Coal No.	Source	Quantity Received (lbs)	Reference Appendix A and B
9	North American Coal Corp., Two barrels Indian Head Mine - Zap, ND	600	12
10	Consolidated Coal Co., Velva, ND Two barrels	900	B
11	Knife River Coal Co., - Savage, MT Five cans	1000	7
12	Westmoreland Coal Co., - Colorado Springs, CO Two barrels Orchard Valley Mine - Paonia, CO	820	4
13	Consolidation Coal Co., Cleveland, Ohio 4 drums Cadiz, Ohio	2000	28
14	Pittson Coal Sales, Greenwich, CT 2 drums Mark Mine, Buffalo Mining Company, Lynchburg, WV	1000	21
15	Pittson Coal Sales, Greenwich, CT 2 drums Elkay Mining Company	1000	2
16	Mid-South Fuel Sales, Oneonta, AL 1 drum Sewanee	400	R
17	Mid-South Fuel Sales, Oneonta, AL Upper Cliff	400	S
18	Mid-South Fuel Sales, Oneonta, AL Rosa	400	T
19	Mid-South Fuel Sales, Oneonta, AL Black Creek	400	W

Table 4-5. Fuels Received (Continued)

Coal	Source	Quantity Received (lbs)	Reference Appendix A and B
20	Westmoreland Resources, Sarpy Creek, MT Two barrels Absaloka Mine	750	7
21	Island Creek Coal Sales Co., Englewood, CO Two barrels Loma Mine	1000	G
22	National Mine Corp., Wayland, KY Two barrels (fully washed mett. coal below 5% ash) Elkorn #3	400	R
23	Island Creek Coal Co., Craigsville, WV Two barrels Upshur Mine, Lower Kittanning Seam	600	V
24	Island Creek Coal Co., Craigsville, WV Two barrels Gauley Eagle #4, Kittanning Seam	600	P
25	Southern Ohio Coal Co., Langsville, OH Two barrels Meigs Mines, Clarion 4A Seam	900	6
26	Cedar Coal Co. Two barrels Ridge 5 Mine, Lower Kittanning, 5-Block Seam	900	2
27	Southern Ohio Coal Co., Langsville, OH Two barrels Martinka #1 Mine, Lower Kittanning, 5-Block Seam	900	28
28	Central Appalachian Coal Co., Two barrels Coalburg #1 Mine, Coalburg Seam	900	T

Table 4-5. Fuels Received (Concluded)

Coal	Source	Quantity Received (lbs)	Reference Appendix A and B
29	Windsor Power House Coal Co. Two barrels Beech Bottom Mine, Pittsburgh #8 Seam	900	1
30	Southern Appalachian Coal Co. Two barrels Freeport Mines, Lower Freeport Seam	900	P
31	Central Ohio Coal Co., Two barrels Muskingum Mine, Meigs Creek #9 Seam	900	27
32	Beltrami Enterprises Inc., Hazleton, PA Two barrels Anthracite	700	Y
33	Island Creek Coal Co., Providence, KY Two barrels Providence No. 1 Mine, No. 9 Seam	689	N

each received, and the relationship of each coal to the test of initial coals selected for testing (see Table 4-4). Analyses for 20 of the purchased coals and for other available coals have been accomplished and are presented in Table 4-6. T4-6

Several other coals have been located and are in the collection/shipping process. These are listed in Table 4-7 with the corresponding information. In addition, the Utah coal was named as the base coal so 300 tons were ordered and received late in the contract year. T4-7

Excellent cooperation of the mine managers and other contractors was afforded EER in acquiring the initially selected coals for testing in the screening studies. Essentially every coal desired for the first year's effort has been received or is in the collection/shipping process. The results from the fuels screening experiments, as well as other factors such as representativeness and performance data availability, will then permit the selection of the fuels to be ordered in larger quantities for single and multiple burner tests.

Table 4-6. Coal Analysis for Coals Available at EER

EER Coal Designation	A ◿	B ⌂	C ⛉	D ○	1 ▽	2 ◸	3 ⬡	4 ◇	5 ◗
Coal Source	TRW COAL #1	TRW COAL # 2	TRW COAL # 3	UTAH	COLSTRIP MONTANA	FARMINGTON NEW MEXICO	FRUITLAND NEW MEXICO	SCRANTON N. DAKOTA	KEMNEREV WYOMING
Ultimate Analysis:									
Carbon, %	71.44	71.57	60.83	68.49	53.16	58.17	52.24	42.02	60.16
Hydrogen, %	4.82	4.94	4.47	5.20	3.43	4.29	3.74	2.71	4.12
Nitrogen, %	1.32	1.33	1.28	1.24	1.09	1.29	1.15	0.54	1.17
Sulfur, %	1.75	1.09	2.98	0.64	0.50	0.75	0.83	0.99	0.50
Ash, %	13.58	11.66	17.90	7.40	9.58	17.96	20.72	7.50	2.84
Oxygen, % (by difference)	5.80	7.54	8.86	10.64	10.97	9.78	10.30	11.28	12.93
Proximate Analysis:									
Moisture, %	1.29	1.87	3.68	6.39	21.27	7.76	11.02	34.96	18.28
Volatiles, %	31.01	32.53	38.19	38.89	30.82	34.95	31.66	28.85	32.65
Ash, %	13.76	11.66	17.90	7.40	9.58	17.96	20.72	7.50	2.84
Fixed Carbon, %	53.94	53.94	40.23	47.32	38.33	39.33	36.60	28.69	43.23
Calorific Value (Btu/lb)	12,502			12,340	9,169	10,391	9,344	6,446	10,935
Forms of Sulfur									
Pyritic, %	1.37				0.21	0.28	0.25	0.32	0.11
Organic, %	0.39				0.29	0.47	0.50	0.65	0.39
Sulfate, %	0.01				0.00	0.00	0.08	0.02	0.00

Table 4-6. Coal Analysis for Coals Available at EER (Continued)

EER Coal Designation	6 ⬡	7 ◇	8 ⬠	9 □	10 D	11 △	12 ◡	13 ◖	14 ⬡
Coal Source	BEULAH N. DAKOTA	COLORADO	HARDIN MONTANA	BEULAH N. DAKOTA	VELVA N. DAKOTA	MONTANA SAVAGE #11	PAONIA CO. #12	CADIZ, OHIO #13B	BUFFALO MARK, W.V.
Ultimate Analysis:									
Carbon, %	43.68	74.32	50.66	43.24	40.09	41.36	67.25	59.41	68.06
Hydrogen, %	2.65	5.10	3.21	2.74	2.26	2.57	4.69	4.25	4.63
Nitrogen, %	0.66	1.53	0.74	0.72	0.71	0.72	1.48	1.03	1.39
Sulfur, %	0.76	2.40	0.61	0.24	0.33	0.27	0.37	7.09	1.57
Ash, %	7.12	7.51	11.26	4.97	7.40	4.61	6.16	18.05	15.50
Oxygen, % (by difference)	12.03	7.11	10.82	13.46	12.41	14.11	12.19	5.88	7.29
Proximate Analysis:									
Moisture, %	33.10	2.03	22.70	34.63	36.80	36.36	7.86	4.29	1.56
Volatiles, %	28.65	34.88	31.16	27.01	26.70	--	39.00	34.87	34.85
Ash, %	7.12	7.51	11.26	4.97	7.40	4.61	6.16	18.05	15.50
Fixed Carbon, %	31.13	55.58	34.88	33.38	29.10	--	46.98	42.79	48.09
Calorific Value (Btu/hr)	7,254	13,425	8,603	7,245	6,587	6,995	11,945	11,038	12,187
Forms of Sulfur									
Pyritic, %	0.35	1.72	0.36	0.03	0.07	0.01	0.02	5.74	0.88
Organic, %	0.39	0.62	0.25	0.21	0.24	0.26	0.35	1.05	0.69
Sulfate, %	0.02	0.06	0.00	0.00	0.02	0.00	0.00	0.30	0.00

Table 4-6. Coal Analysis for Coals Available at EER (Concluded)

EER Coal Designation	15 ⬠	16 ⬯	17 ✚	18 ⌂	19 ⬡	20 ◹
Coal Source	ELKAY W.V. #15	SEWANEE ALABAMA	UPPER CLIFF, AL	ROSA ALABAMA	BLACK CRK. ALABAMA	HARDIN MONTANA
Ultimate Analysis:						
Carbon, %	73.52	79.24	76.94	74.72	80.27	53.97
Hydrogen, %	4.90	4.33	4.34	4.36	5.09	3.70
Nitrogen, %	1.39	1.36	1.42	1.60	1.75	0.79
Sulfur, %	2.45	0.75	1.27	0.96	0.74	0.85
Ash, %	11.61	8.73	9.49	6.79	4.45	8.62
Oxygen, % (by difference)	5.53	3.08	3.54	3.55	5.45	11.58
Proximate Analysis:						
Moisture, %	0.60	2.51	3.00	8.02	2.25	20.49
Volatiles, %	33.35	20.39	20.44	21.81	28.28	33.24
Ash, %	11.61	8.73	9.49	6.79	4.45	8.62
Fixed Carbon, %	54.44	68.37	67.04	63.38	65.02	37.65
Calorific Value (Btu/lb)	13,115	13,749	13,254	13,394	14,284	9,229
Forms of Sulfur						
Pyritic, %	1.59	0.24	0.50	0.43	0.07	0.56
Organic, %	0.81	0.45	0.61	0.47	0.67	0.29
Sulfate, %	0.05	0.06	0.16	0.06	0.00	0.00

Table 4-7. Coals to be Delivered

- Beltrami Enterprises, Inc.
  Pennsylvania Anthracite 9% Ash, 0.5S, 4.5 Vol.
  One barrel each pea/nut 86.5% C, 14,000 Btu/lb

- Virginia Iron, Coal and Coke Co.
  - Splashdam Seam - High S
  - Jawbone Seam - High S
  - Lyons Seam - Low S

- Shell Development Co.
  Texas Lignite

- American Electric Power Service Corporation

  1. Lower Kittanning - Five-Block coal from the Martinka No. 1 Mine near Fairmont, West Virginia, Southern Ohio Coal Co.
  2. Lower Kittanning - Five Block coal from the Ridge 5 Mine near Chelyan, West Virginia, Cedar Coal Co.
  3. Clarion 4A coal from the Meigs mines near Wilkesville, Ohio, Southern Ohio Coal Co.
  4. Lower Freeport coal from the Freeport mines near Julian, West Virginia, Southern Appalachian Coal Co.
  5. Pittsburgh No. 8 coal from the Beech Bottom Mine near Wheeling, West Virginia, Windsor Power House Coal Co.
  6. Coalburg coal from the Coalburg No. 1 Mine near Montgomery, West Virginia, Central Appalachian Coal Co.
  7. Meigs Creek No. 9 coal from the Muskingum Mine near Cumberland, Ohio, Central Ohio Coal Co.

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5.0 LOW NO_X RESEARCH BURNERS

Two different burner systems have been tested to date. These are:

- A burner with a divided secondary throat which allows control of axial and tangential velocity in two annular air streams. Fuel is injected axially from an annulus surrounding a central oil gun which is used as an ignition source.
- A simple double concentric burner with fixed swirl vanes in both the annular fuel and secondary air channels. The fixed vane impeller was introduced to enhance flame stability to provide internal recirculation at low secondary airflow. This burner design was selected because of ease of construction in providing for exact geometric and velocity similarity at three scales.

The simple double concentric burner was utilized during the first year's efforts.

The fuel injector design, secondary air swirl, velocity ratio between primary and secondary flows, burner exit geometry, location of outboard staged air jets and outboard staged momentum were designed to meet the following practical process parameters:

- The combustion system must be suitable for the existing water-wall envelope, i.e., the flame shape must be similar to that for which the combustion chamber was originally designed. In addition, the burner windbox system should be easily accommodated without major modifications to the water-wall.
- The reduction in pollutants should not be accompanied by a decrease in thermal efficiency, or an increase in any related pollutant. Since modern utility boiler practice achieves almost complete combustion, the low NO_x system should not cause an unprecedented increase in either carbon monoxide or unburned carbon.

- The modification of the combustion system to provide for low NO_x coal burners should not increase the boiler downtime due to slagging or water-wall corrosion.
- The low NO_x coal burner control system should be equivalent to the general state-of-the-art of burner controls. If a new generation of control equipment would be required, then the cost of NO_x control would increase considerably.
- The control of NO_x should not be accompanied by an increase in any other pollutant.

F5-1

The simple double concentric burner design shown in Figure 5-1 accomplishes these requirements by incorporating the following features:

- Three independently-controlled air streams to divide the total combustion air into:
    1. The primary air carrying the coal.
    2. A concentric secondary air stream.
    3. Four outboard staged air streams.
- An annular fuel injector with a retractable oil gun on the burner axis.
- The swirl level of the secondary air stream controlled by varying the adjustable swirl vanes. Thus, the total swirl level can be varied from zero to a maximum dictated by the angle of the adjustable swirl vanes.
- Interchangeable ceramic burner exits.

The double concentric burner shown in Figure 5-1 is a simple design incorporating practical features to provide ease of manufacture and operation and to allow for the most straightforward interpretation of results. In order to develop scale criteria the burners were designed at 12.5, 50 and 100 x 10^6 Btu/hr firing rates. The principle of geometric similarity with constant velocity was used for scale design. In background studies (Ref. 5-1) this scaling procedure resulted in similar low NO_x performance between burners of differing scale whereas a combination

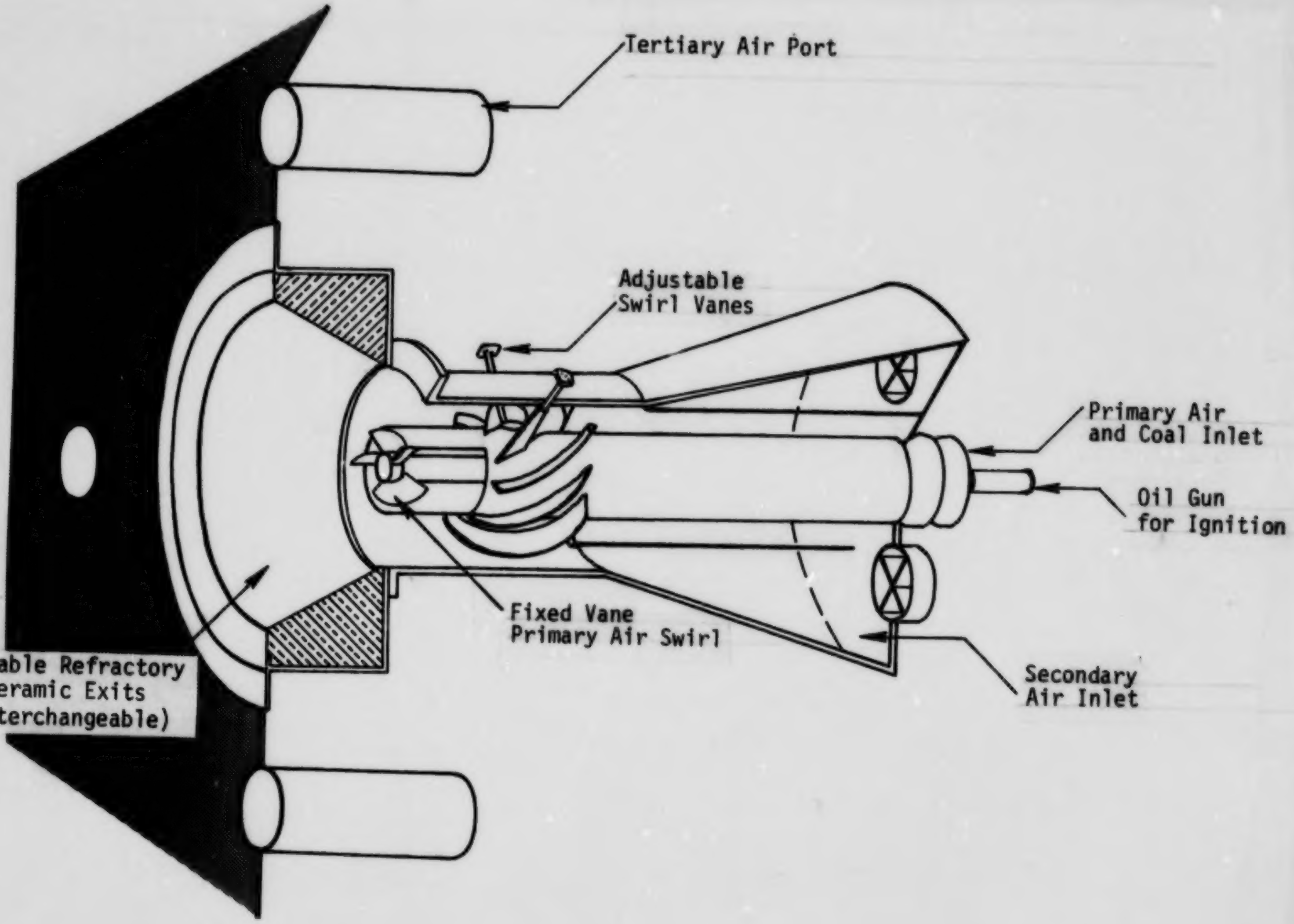

Tertiary Air Port
Adjustable Swirl Vanes
Primary Air and Coal Inlet
Oil Gun for Ignition
Fixed Vane Primary Air Swirl
Secondary Air Inlet
Castable Refractory Ceramic Exits (Interchangeable)

Figure 5-1. Low NO_x Development Burner - Simple Double Concentric Burner Design.

of constant velocity and equal residence time approach did not yield as low of NO_x values when scaling down from 50 to 12.5 x 10^6 Btu/hr. The three scales of burner each employed similar distributions of tangential velocity and similar locations of tertiary air inlets. A summary of the specific design dimensions for each burner is provided in Table 5-1.

For a given load and overall excess air, velocities in the various channels vary as the burner zone stoichiometry is varied. Decreasing the primary zone stoichiometry decreases the secondary velocities as the tertiary velocities as the tertiary velocity is increased. Furthermore, as the load is reduced, the secondary and tertiary air velocities must be reduced if the burner zone stoichiometry is to be maintained. These variations in axial velocity will affect the flame characteristics, and therefore, flame stability and NO_x. This could be compensated for by variation in the secondary swirl which has a strong affect on the near-field mixing characteristics. A graph of the swirl index (ratio of tangential to axial momentum) vs. primary zone stoichimetry for two swirl angles (0 and 45 degrees) are shown in Figure 5-2. This flexibility allowed the three basic flow patterns shown in Figure 5-3, observed in both cold and hot flow, to occur. The various flames are described as:

- Type A with all axial flow except for an annular toroidal recirculation zone which provides for flame stability.
- Type B with an axial toroidal recirculation zone.
- Type C in which the flow is attached to the combustion chamber wall producing a wall jet.

The transition from A through C occurs as the swirl level in the outer channel is increased. Figure 5-3 also presents sketches of two general flame types which were obtained with the double concentric burner during testing in the LWS. The shorter flame is much more compatible with existing boiler designs.

Table 5-1. Burner Dimensions

DESIGN VARIABLES	12.5 M Btu/hr	50 M Btu/hr	100 M Btu/hr
• Fuel Injector			
- Annulus Diameter (in.)	5½	10 1/2	15 3/4"
- Area (in^2)	21	86	195
- Fixed Swirl Angle (deg.)	45	45	45
• Secondary Air Channel			
- Annulus Thickness (in.)	4 7/8 (10 3/8 ID-5½")	9 1/2 (20" - 10½")	12 1/4 (28" - 15 3/4
- Area (in^2)	61	228	415
- Axial Position (recess) (in)	0	0	0
- Variable Swirl Angle (deg.)	60^0	60^0	60^0
• Tertiary Ducts			
- Distance from burner CL (in.)	22	44	62
- Spacing Around Burner	90^0	90^0	90^0
- Injection Angle (deg.)	4	4	4
- Axial Location	6"	12"	16
- Number of Ports	113	452	804
- Diameter (in.)	0	0	0
- Total Area (in^2)	0	0	0
• Throat & Exit			
- Throat Diameter (in.)	10 3/4	20	28
- Throat Area (in^2)	91	314	615
- 1/1 Angle of Exit (deg.)	25	25	25
- Length of Exit (in.)	9	19	27
• Oil Gun (ignitor)			
- Nozzle Type	Hago 80^0	Hago 80^0	Hago 80^0
- Capacity GPH	30	330	330
- Axial Position (Recess)	0	0	0

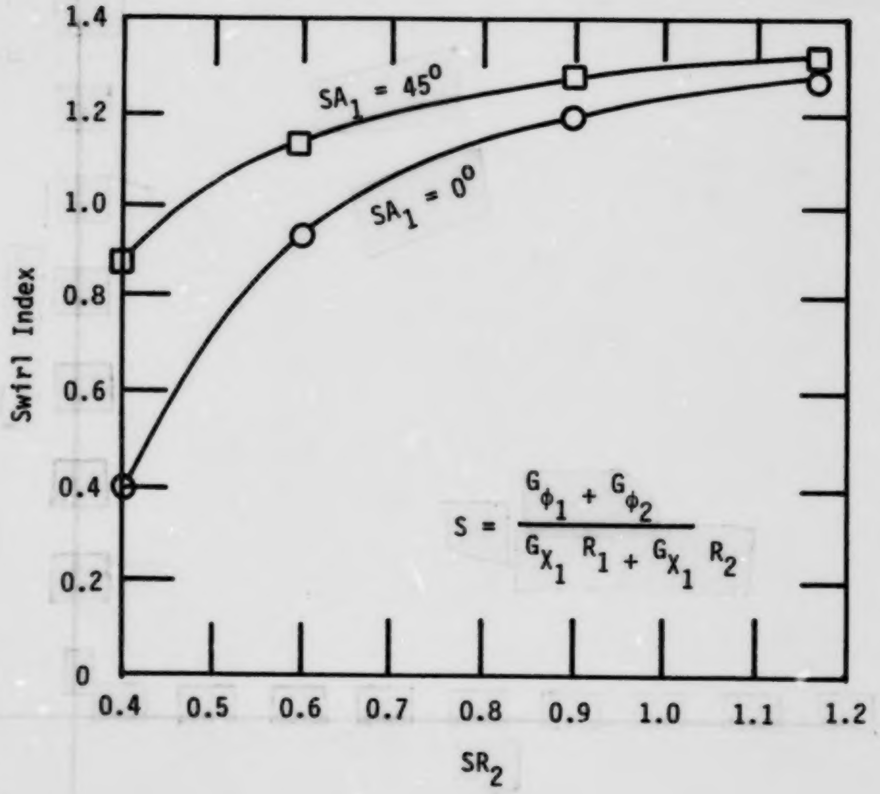
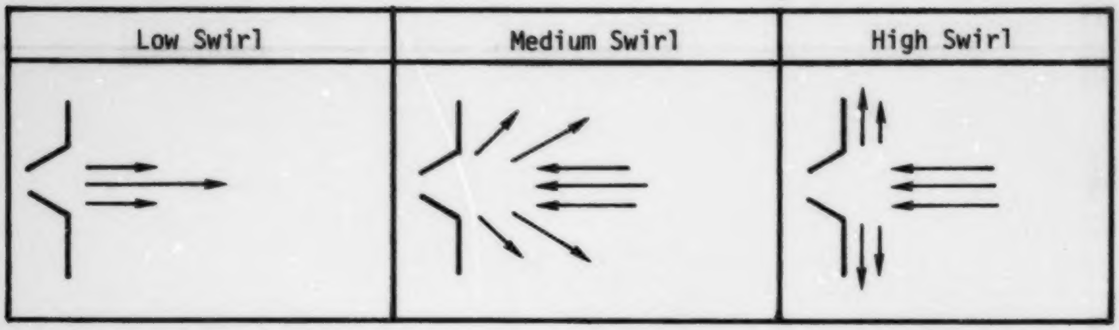
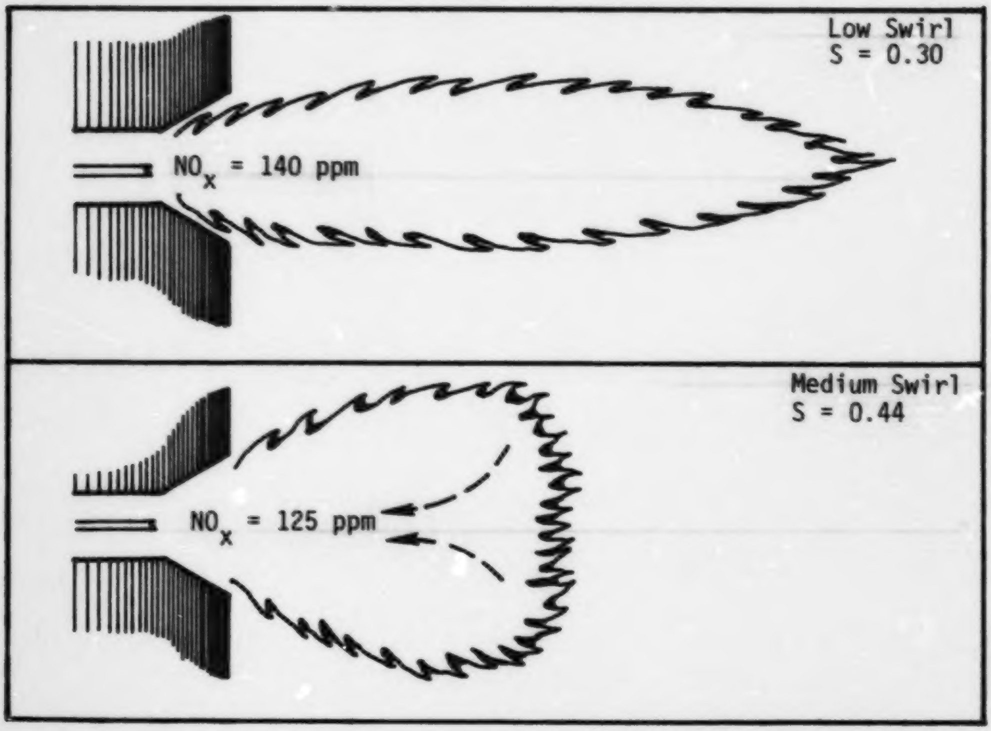


Figure 5-2. Swirl Characteristics for the Double Concentric Burner Design.


Low Swirl
Medium Swirl
High Swirl

A.) Flame Types


Low Swirl
S = 0.30
NO_x = 140 ppm
Medium Swirl
S = 0.44
NO_x = 125 ppm

B.) Low NO_x Flame Shapes

Figure 5-3. Flame Characteristics for DMB.

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6.0 EXPERIMENTAL STUDIES

The experimental efforts encompass four tasks. As shown in Figure 6-1, three of these tasks involve extension of the low NO_x technology to include a wide range of coals, optimization of reactor schemes leading to advanced low NO_x concepts, and integration of this information into single and multiple burner designs. Task 5 (Figure 6-2) involves the testing of commercial burners to provide a comparison of operation between commercial burner designs and the low NO_x burners in the large-scale facility. In this way an estimate can be made of the difficulties and potential emission levels that might be expected if the low NO_x burner were to be installed in field operating boilers. Further, the results will also provide some insight into the limits of applicability of the research combustor for full-scale burner development.

F6-1
F6-2
1.5

6.1 Results

The experimental efforts have concentrated on: 1) screening of a range of fuels to define the effect of fuel properties on NO_x formation under differing fuel/air contacting conditions and preliminary data with research low NO_x burners to ascertain whether the impact of fuel properties is similar under more practical operating conditions; and 2) a brief study of combined NO_x/SO_x control aimed at application of the low NO_x burner together with dry sorbents for in situ SO_x removal. For the purpose of showing the progession of the technology from one scale to another the results given below are presented by technical areas rather than by Task. Therefore, the first subsection describes the results obtained to define the effect of fuel properties on NO_x emissions at three scales (0.1, 12.5 and 100 MBtu/hr). The second subsection describes the dry sorbent results obtained at small-scale (100,000 Btu/hr) and pilot-scale (12.5 MBtu/hr). In the third subsection the initial efforts to define control systems approaches for the burner airflows are discussed and the last subsection describes the commercial burner efforts to date.

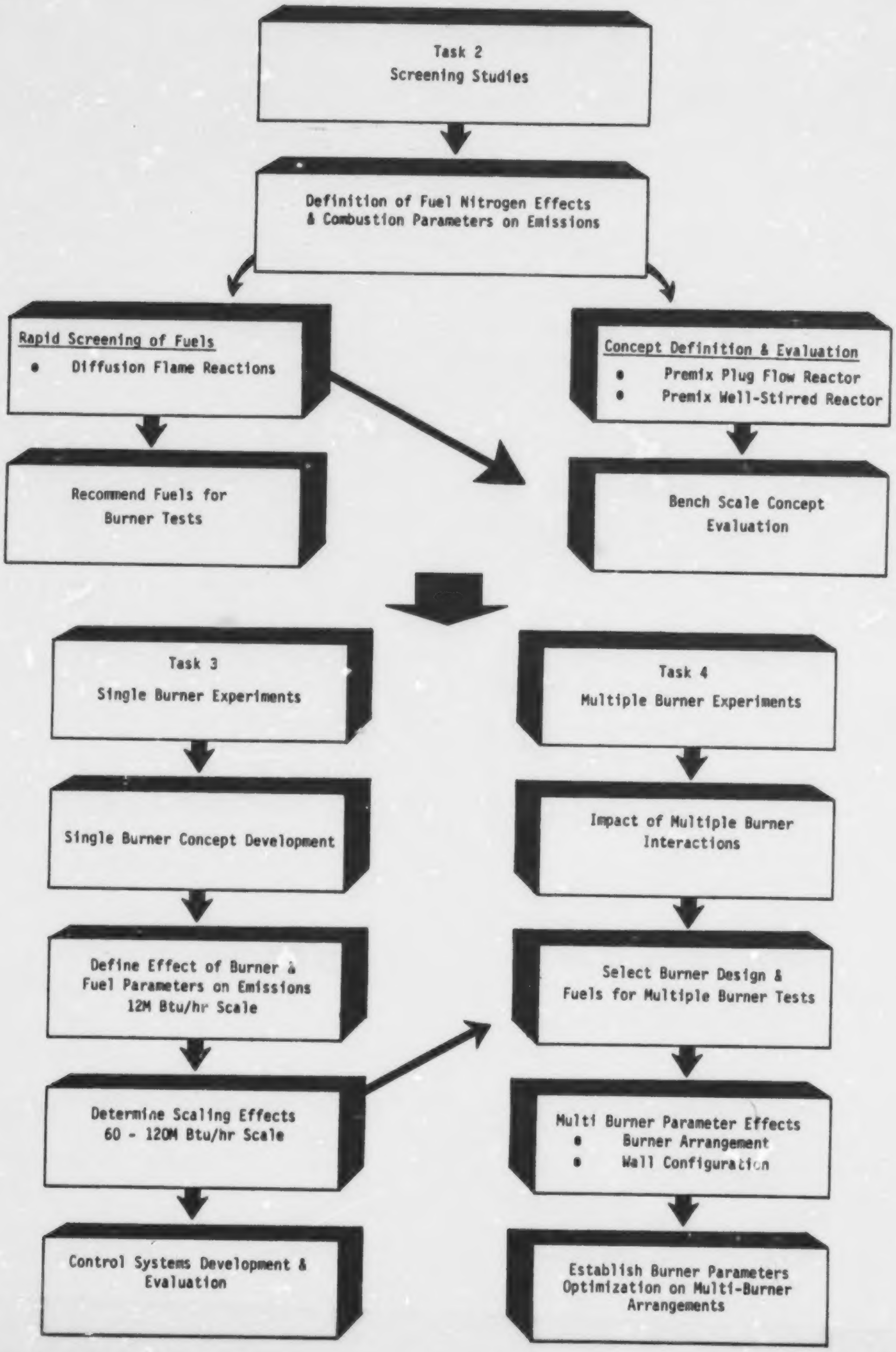

Task 2
Screening Studies
Definition of Fuel Nitrogen Effects
& Combustion Parameters on Emissions
Rapid Screening of Fuels
• Diffusion Flame Reactions
Concept Definition & Evaluation
• Premix Plug Flow Reactor
• Premix Well-Stirred Reactor
Recommend Fuels for
Burner Tests
Bench Scale Concept
Evaluation
Task 3
Single Burner Experiments
Task 4
Multiple Burner Experiments
Single Burner Concept Development
Impact of Multiple Burner
Interactions
Define Effect of Burner &
Fuel Parameters on Emissions
12M Btu/hr Scale
Select Burner Design &
Fuels for Multiple Burner Tests
Determine Scaling Effects
60 - 120M Btu/hr Scale
Multi Burner Parameter Effects
• Burner Arrangement
• Wall Configuration
Control Systems Development &
Evaluation
Establish Burner Parameters
Optimization on Multi-Burner
Arrangements

Figure 6-1. Experimental Plan and Logic for Burner Development.

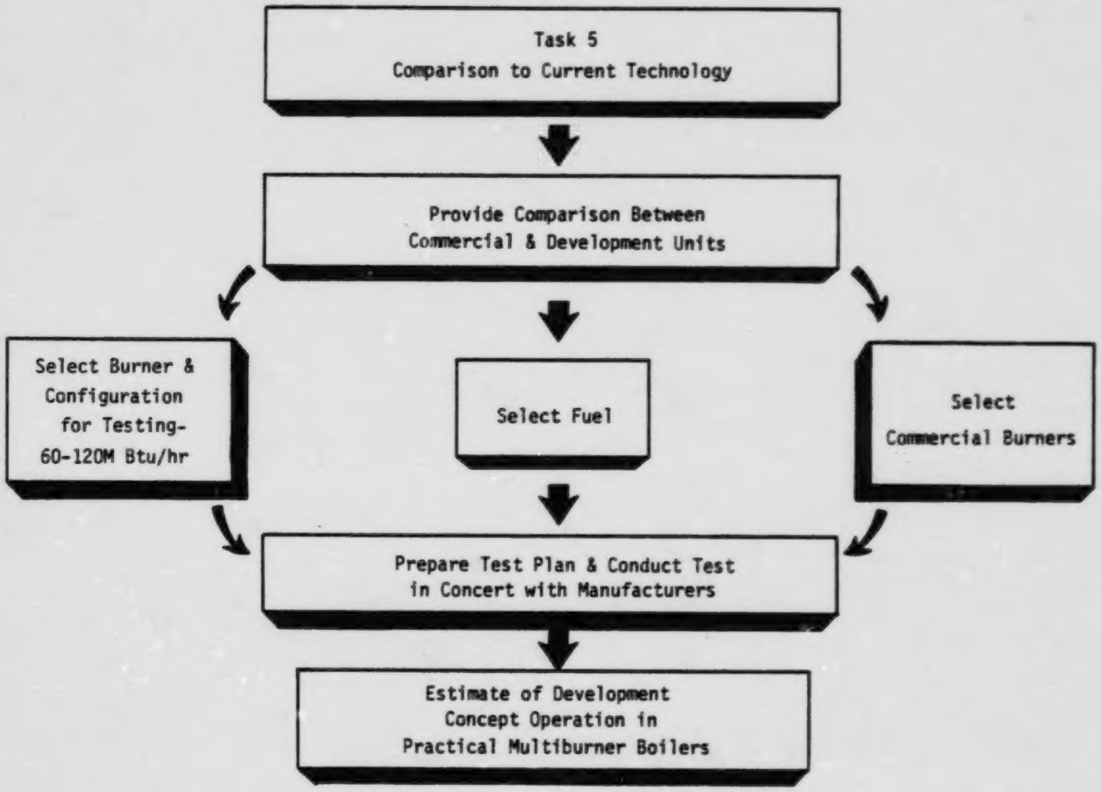

Task 5
Comparison to Current Technology
Provide Comparison Between
Commercial & Development Units
Select Burner &
Configuration
for Testing-
60-120M Btu/hr
Select Fuel
Select
Commercial Burners
Prepare Test Plan & Conduct Test
in Concert with Manufacturers
Estimate of Development
Concept Operation in
Practical Multiburner Boilers

Figure 6-2. Experimental Plan Logic for Commercial Burner Study.

6.1.1 Fuels Study

Small-Scale Reactor

The small-scale studies have concentrated upon the screening of a large number of fuels to define any gross difference in their emission characteristics which could be related to their physical and/or chemical properties. In addition, using the baseline coal, experiments have been conducted to determine the effect on NO_x emissions of excess air, flame zone temperature, particle size, and fuel/air contacting under unstaged conditions. Under staging conditions variations in stoichiometry/residence time and fuel/air contacting have also been investigated.

In order to assess the conversion of fuel nitrogen to NO it is necessary to eliminate the production of NO from molecular nitrogen (thermal NO). For all tests reported herein, unless otherwise noted, thermal NO production was prevented by the use of artificial oxidants which did not contain molecular nitrogen, thus any NO appearing in the exhaust was formed either directly or indirectly from the nitrogen contained in the fuel. The artificial oxidant consisted of mixtures of argon, carbon dioxide, and oxygen to give the appropriate oxygen concentration and adiabatic flame temperature. It should be noted that this method is not free from criticism and has two major drawbacks:

1. The formation of fuel NO may be affected by the large excess of nitrogen molecules present when air is used as the oxidant.
2. The addition of CO_2 which is used to balance flame temperatures because of the different heat capacities of argon and nitrogen may affect H, OH and O concentrations and this affect is most likely to have a strong influence upon reactions involving nitrogenous species under fuel-rich conditions.

Although the use of artificial oxidants may not be ideal, this method was utilized in these experiments since it represents the most suitable method available to date for assessing fuel nitrogen conversion during the combustion of real fuels. However, it should not be expected that the difference between NO emissions measured in air and argon atmospheres necessarily represents thermal NO production when that fuel in burned in air.

Excess Air Dependence. During the program all coals are being evaluated in the small-scale combustor with the premixed reactor as an initial screening tool. From these results coals are then selected for more detailed study. To date seven coals have been tested over a range in excess air levels. A listing by rank for these coals is provided in Figure 6-3. Note that these coals include two medium volatility, one high volatility-A, and two high volatility-B bituminous grade coals as well as two lignites. In addition, these coals range in nitrogen levels (as received) from 0.54 to 1.75 percent, and sulfur levels from 0.17 to 2.98 percent. F6-3

The coals were pulverized to give a size distribution of 70 percent to pass through 200 mesh. The pulverized coals were then placed in the feed hopper and pneumatically delivered to the premixed reactor. The coal was thoroughly mixed with the preheated combustion air (700^{0}F) before passing into the ignition zone of the reactor where pyrolysis, devolatilization and combustion occurred. The combustion process with this reactor occurs in a plug flow manner with little or no backmixing of products. After completion of combustion the gases then enter the stack where continuous monitoring of emissions and specific combustion products were measured. The results presented in Figure 6-4 show that when combusted in this manner all coals behaved similarly with increasing NO_x emissions as excess air levels were increased. It is interesting to note that while all coals behaved in a similar manner, the levels of gaseous NO_x emissions did not necessarily increase with increasing fuel nitrogen. Further, the slope of the various curves appear to be almost identical suggesting that the overall mechanisms controlling the conversion are similar regardless of the fuel grade. F6-4

Flame Zone Temperature. Flame zone temperature was varied by changing the Ar/CO_2 ratio of the oxidizer gas (O_2, CO_2, Ar). The results shown in Figure 6-5 reveal that as the flame zone temperature was decreased (increasing percent CO_2) the fuel NO_x emissions also decrease. Further, F6-5

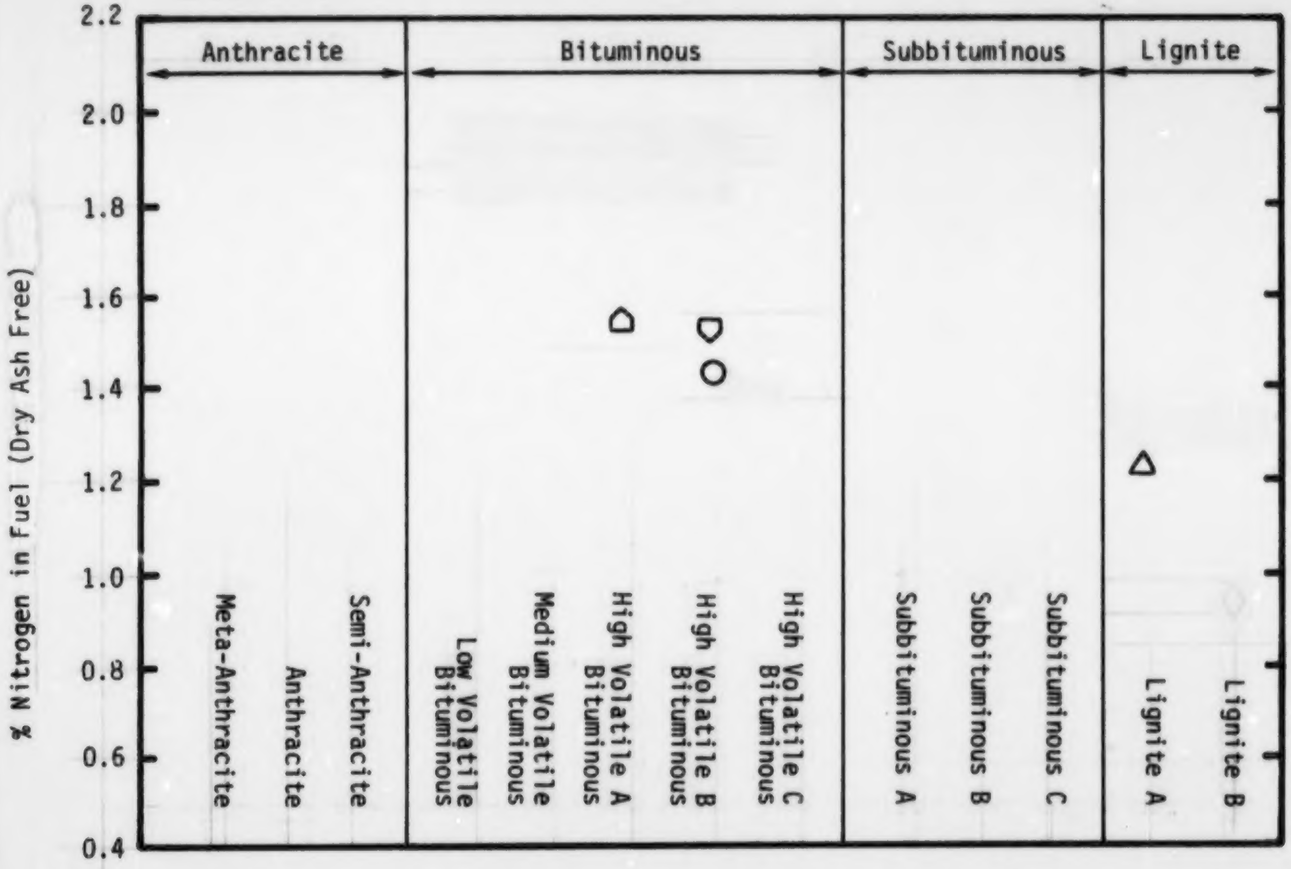
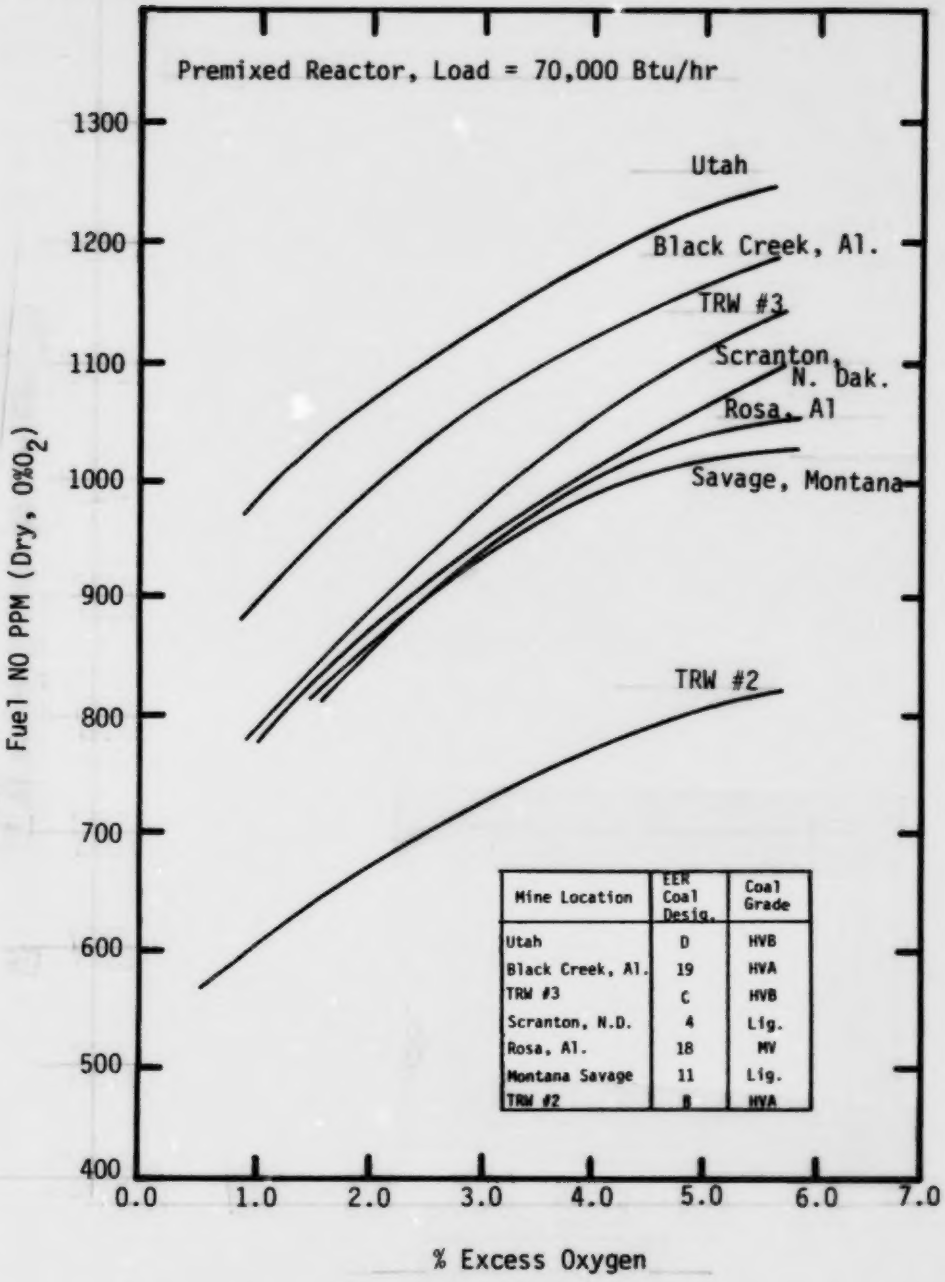


Figure 6-3. Range of Fuel Grade for Coals Currently Studied (Symbols refer to Table 4-6).



Mine Location	EER Coal Desig.	Coal Grade
Utah	D	HVB
Black Creek, Al.	19	HVA
TRW #3	C	HVB
Scranton, N.D.	4	Lig.
Rosa, Al.	18	MV
Montana Savage	11	Lig.
TRW #2	B	HVA

Figure 6-4. Excess Air Dependence (unstaged) on NO_x Emissions for various coals.

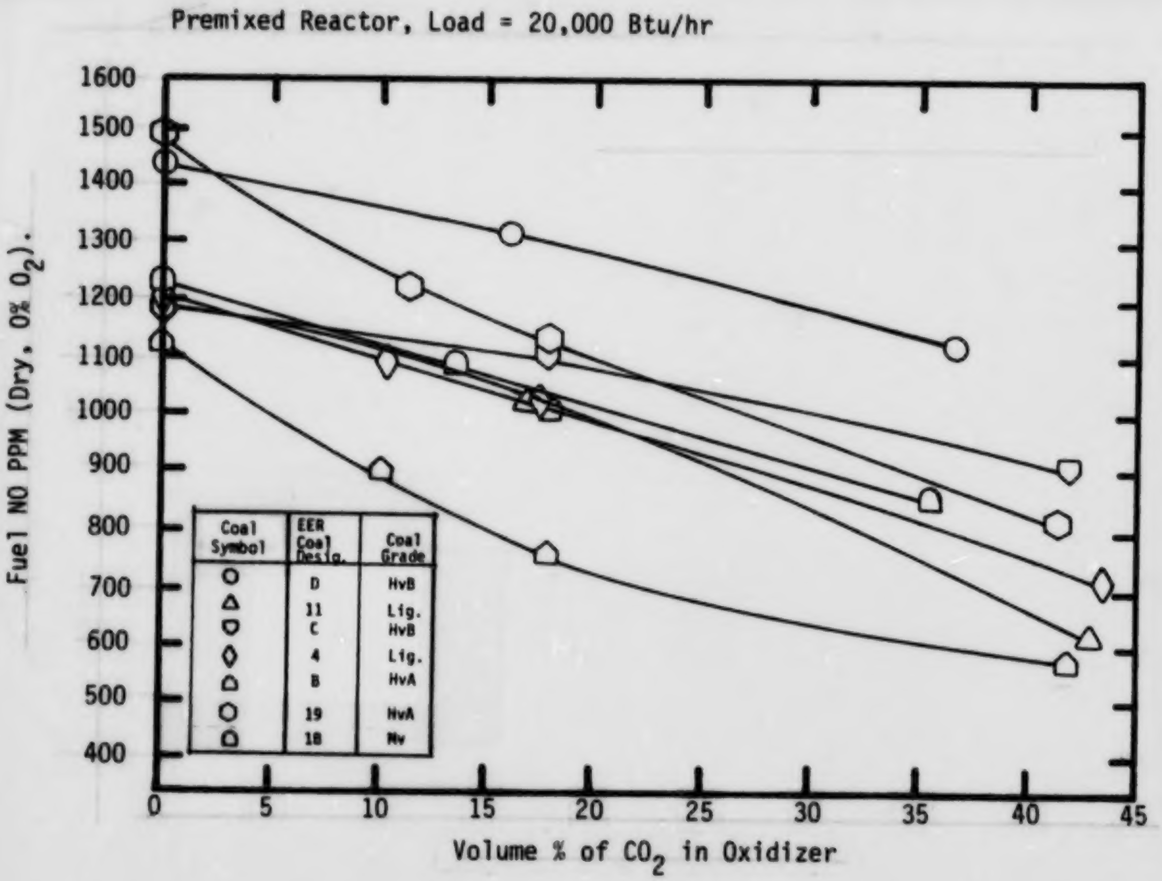


Figure 6-5. Effect of Flame Zone Temperature on NO_x Emissions for Several Coals.

the dependence of NO_x emissions on flame zone temperature appears to be quite large suggesting that operating parameters such as air preheat, fuel properties and fuel/air contacting rates such as moisture should affect fuel nitrogen conversion. Since all coals experience the same approximate heating rate, the results could be attributed to the variation of fuel nitrogen between the volatile and the char fractions as a function of heating rate.

Particle Size. An initial series of tests were conducted to determine the effect of coal particle size on NO_x emissions over a range of stoichiometry. Two particle size and distributions were employed in these experiments: 1) a narrow cut with an average particle size of 165μ (150 to 178μ); and 2) a normal coal distribution 70 percent less than 200 mesh (64μ). For the latter case then the largest particles are 178μ and 70 percent of the coal mass is distributed at sizes less than 64μ. As such, the normal grade of pulverized coal represents a smaller overall particle size.

The coal particles were premixed with air then subjected to a staged reaction sequence wherein the first stage stoichiometry was varied from 0.4 to 1.25 keeping the overall stoichiometry at 1.25. With this scheme the importance of the initial reaction zone as well as the burnout zone could be studied. The results shown in Figure 6-6 reveal that as the primary zone stoichiometry decreases the smaller particle sizes tend to convert a smaller fraction of their fuel nitrogen to NO_x than do the larger sizes, although for these experiments the difference was not great. It is possible, however, that for smaller average particle sizes the difference in the SR = 0.5 range may be even greater.

Initial Fuel/Air Mixing. The unstaged results wherein the oxidant was synthetically made (Ar, CO_2, O_2) are plotted in Figure 6-7 and clearly demonstrate under these types of reaction conditions the strong dependence of fuel NO_x on the fuel/air contacting process. This result is not unexpected and can be attributed to the fact that as the coal/air mixing varies from premixed to an axial diffusion flame there is less

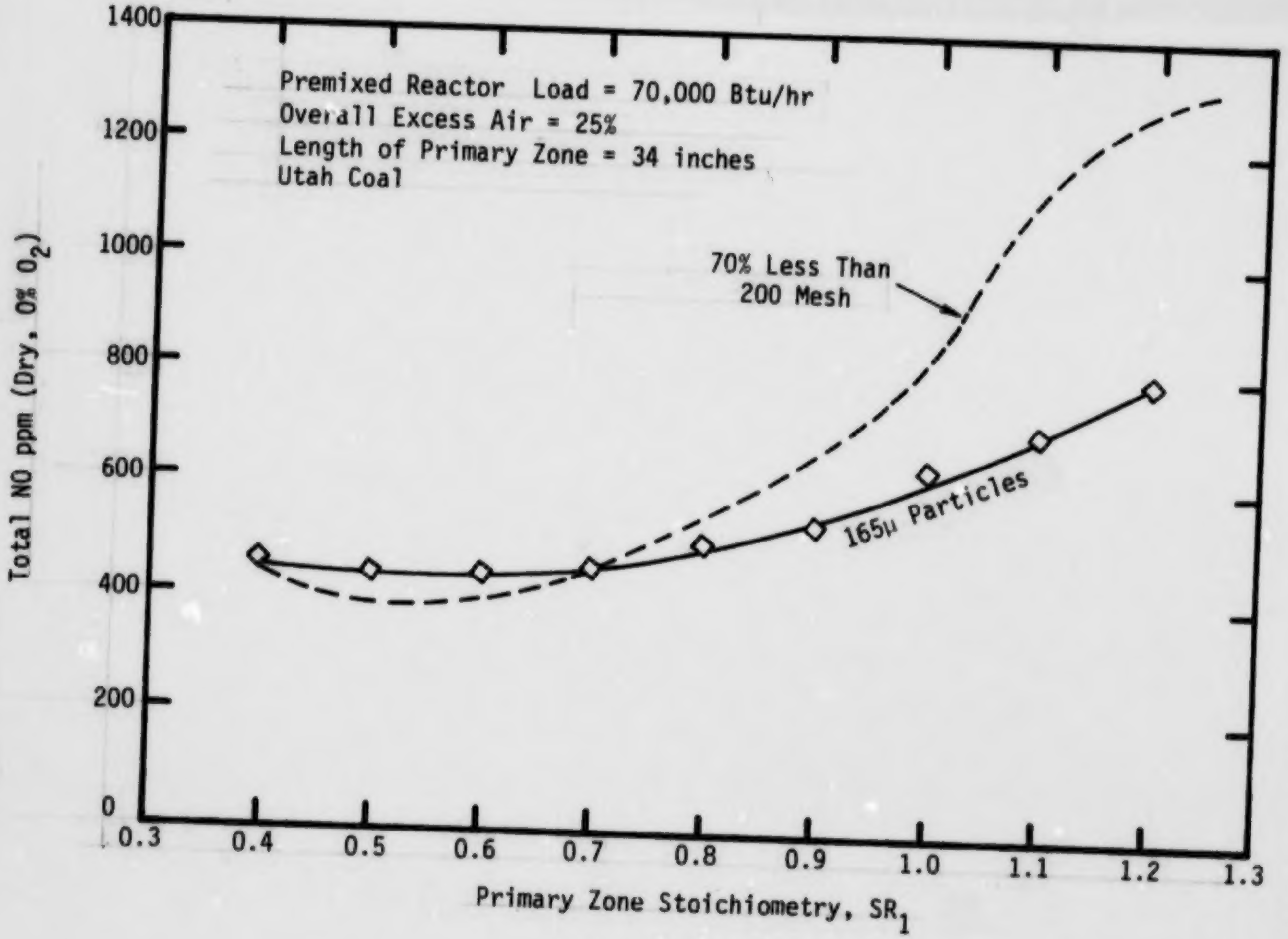


Figure 6-6. Effect of Mean Particle Size on NO_x Emissions as a Function of Primary Zone Stoichiometry.

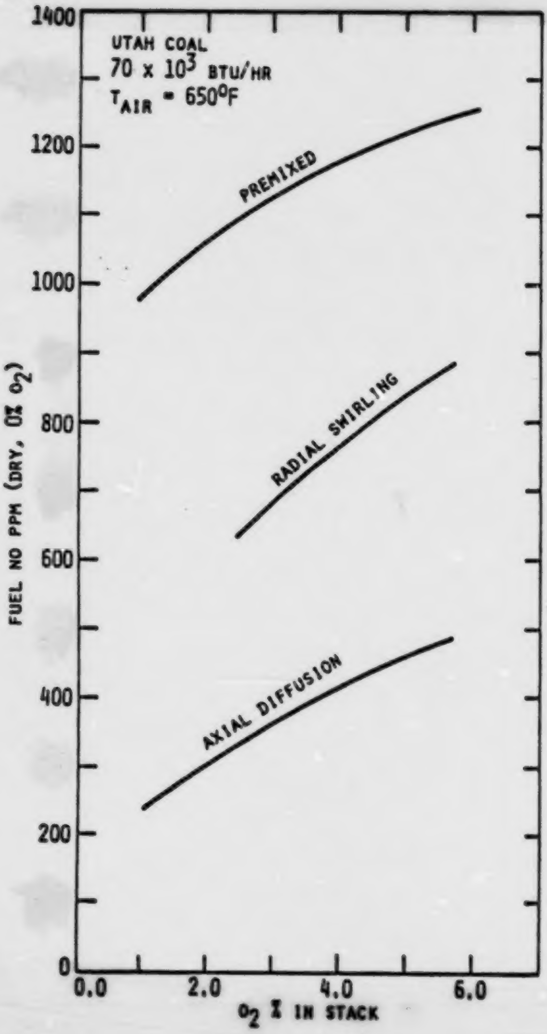


Figure 6-7. Influence of Initial Fuel/Air on NO_x Emissions Obtained Using Various Reactor Types.

oxygen in contact with the volatile fuel nitrogen fractions, and therefore, the formation of N_2 from the volatile nitrogenous specie is maximized.

Different fuel/air mixing sequences were obtained by using three reactor types:

- Premixed reactor
- Axial diffusion reactor
- Radial swirling reactor

In these experiments the "normal" grades of pulverized coal were used. For the first series of experiments an unstaged reactor sequence was employed so that the burners were used as the sole means for controlling the fuel/air contacting history. During these tests then, the entire furnace volume of the combustor was used as a single stage. Staged tests were also conducted wherein the reactor input conditions represented the first stage stoichiometry and the fuel/air contacting process for the initial 34 inches of the reactor was controlled by the burner. Secondary air was then injected bringing the overall stoichiometry to 1.25. Fuel/air contacting in the second stage was therefore controlled by the characteristics of the air injection system. The remainder of the furnace was used to complete the reaction and flue gas measurements were made at the stack. As noted in Figure 6-8, the first stage stoichiometry was varied from about 0.4 to 0.9 while the overall excess air remained constant at 25 percent. The results do not show the same relative ranking of reactors with respect to NO_x emissions as did the unstaged results and the relative differences in levels are considerably. In addition, the levels of NO_x emissions under staged conditions is about 50 percent lower than when unstaged. These results are difficult to interpret because the actual rich first stage residence time will depend upon the fuel/air mixing reactor type. It appears, however, that a backmixed first stage gives lower final emissions than either the premixed or the axial diffusion flame.

F 6-8
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Stoichiometric Ratio and Residence Time (Staged). The effect of stoichiometric ratio and residence time on flue gas NO_x emissions were studied by varying both the length of the first stage reaction zone and

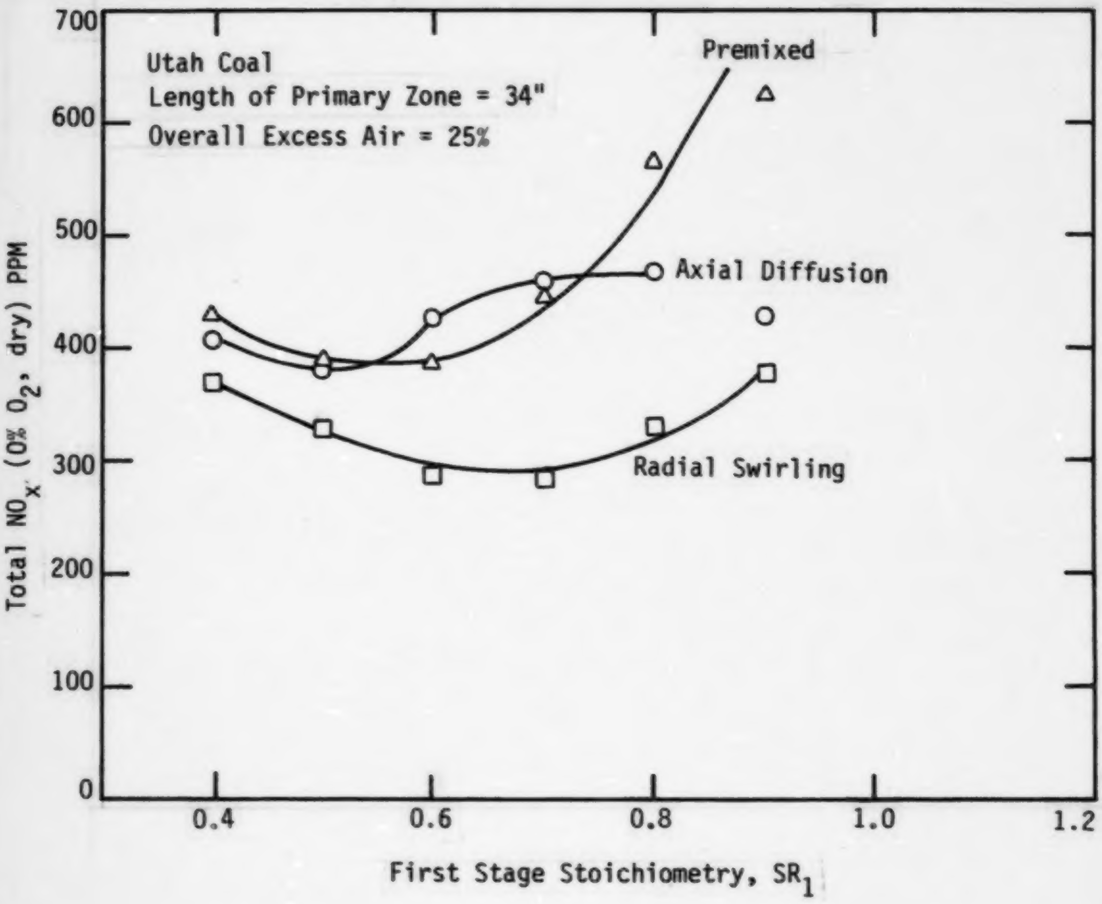


Figure 6-8. Effect of Fuel Air Contacting Under Staged Operating Conditions.

the first stage stoichiometry keeping the overall stoichiometry constant. The results presented in Figure 6-9 were obtained at three different first stage reactor lengths of 21, 34 and 51 inches over a range of first stage stoichiometries from 0.4 to 0.95. For these tests the overall stoichiometry was constant at 25 percent excess air, and air was used as the oxidant. Note that the NO_x emissions characteristics are similar at all three first stage reactor lengths, first decreasing as the first stage stoichiometry is reduced until a minimum in NO_x is reached and then the NO_x increases as SR is further decreased. When plotted in the manner presented in Figure 6-9 the minimum value of NO_x occurs at differing first stage stoichiometries for each reactor length. This suggests that obtaining the lowest possible NO_x levels will require optimizing the sequence for air addition since both stoichiometry and residence time are interdependent.

F6-9

As one step toward investigating a more distributed air addition sequence a three-stage reactor scheme was also studied. In this case the first stage was held constant at 21 inches, the second stage at 34 inches and the remaining length of the combustor (i.e., 25 inches) represented the third stage. In this case the first stage stoichiometry was varied while the second and third stage stoichiometries were held constant at 0.8 and 1.25, respectively. The results for the three-stage reactor sequence are plotted in Figure 6-10 and show that the more distributed air addition results in even lower emission than the two-stage systems. For comparison, the 34-inch length first stage results for the two-stage reactor are also shown on Figure 6-10. Comparison of these results clearly demonstrate that control of the rate of fuel/air mixing is, therefore, a key requirement to minimize NO_x emissions from coal-fired systems.

F6-10

A brief series of experiments were also conducted to determine if any gross changes in NO_x emissions would occur with various coals having large variations in fuel properties. For these tests the two-stage reaction sequence was employed with the first stage 34 inches long. The results are shown in Figure 6-11 for all five coals. Note that the NO_x characteristics under varying first stage stoichiometry conditions are

F6-11

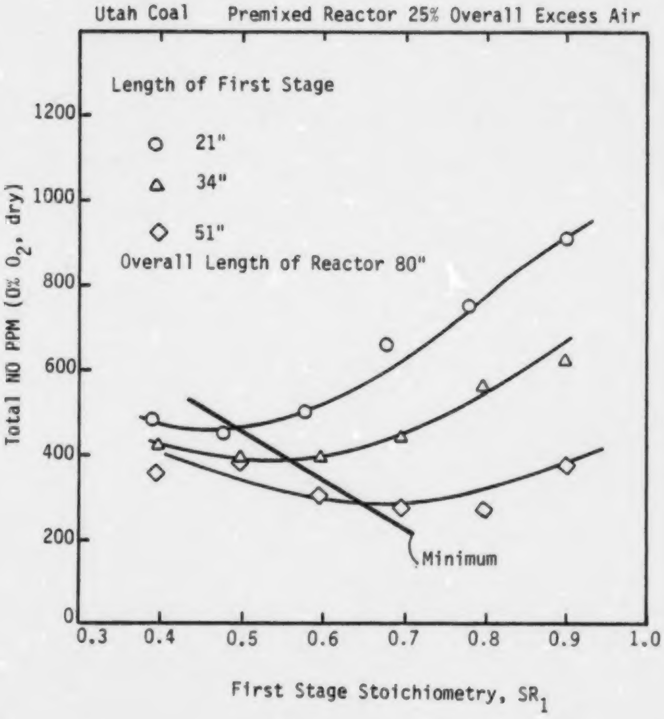


Figure 6-9. Effect of SR and Residence Time on NO_x Emissions.

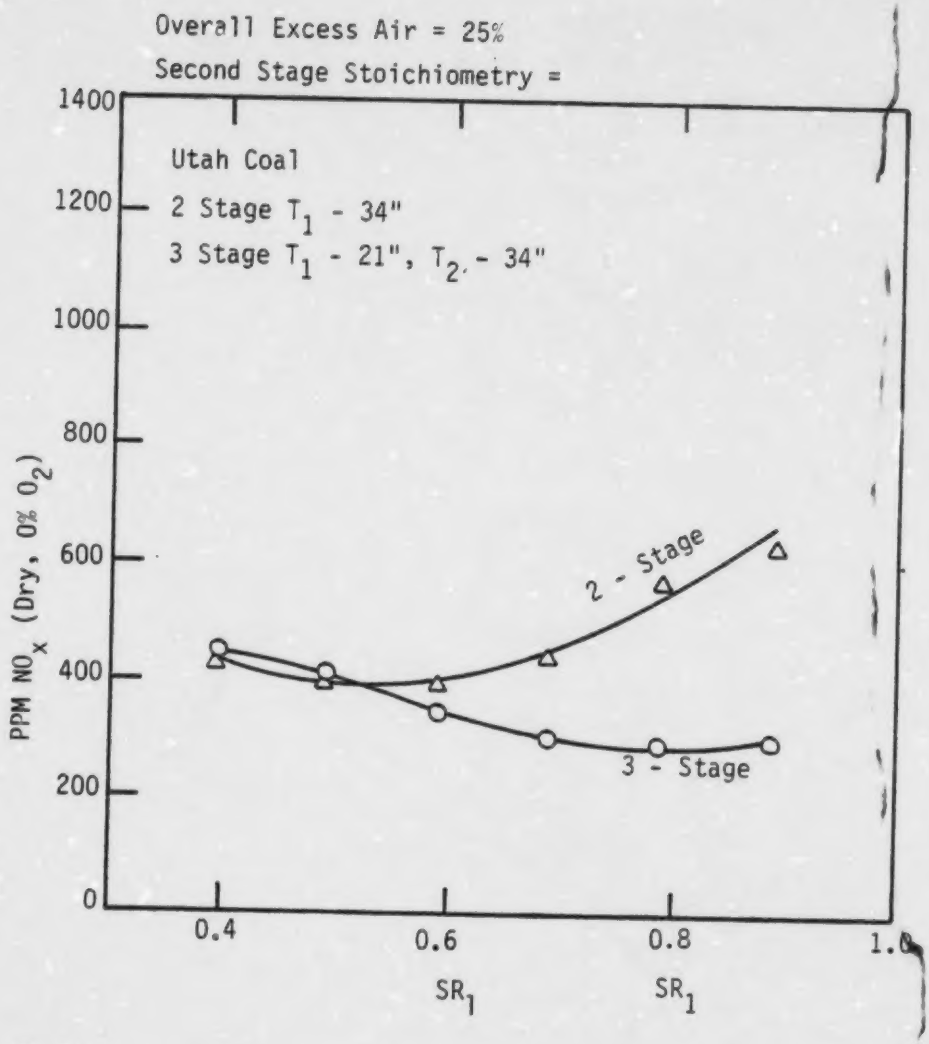


Figure 6-10. Effects of Distributed Air Addition on NO_x Characteristics.

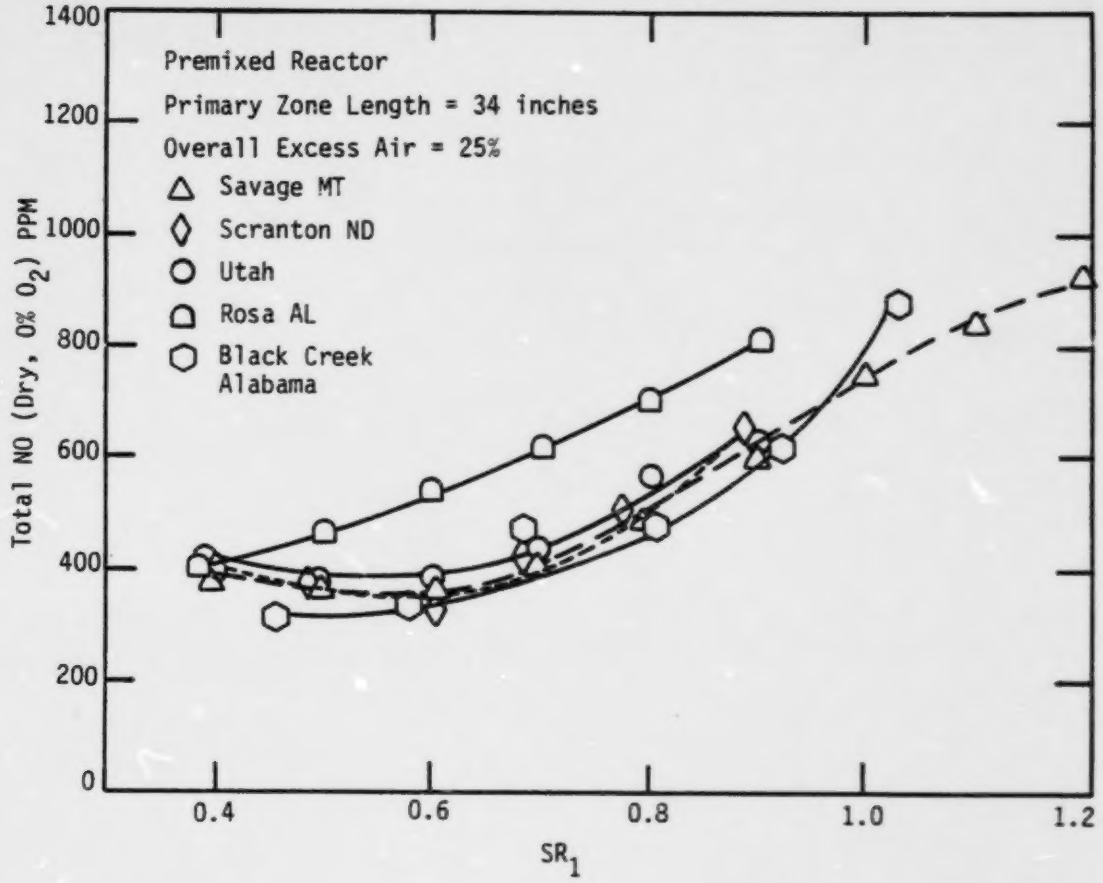


Figure 6-11. Effect of Coal Composition on NO_x Emissions Under Staged Operating Conditions.

quite similar suggesting that the optimum reaction sequence will not be strongly fuel-dependent. These results are indeed encouraging in that it appears that dramatic changes in burner design may not be necessary when changing from one fuel grade to another.

Single Burner Experiments. The purpose of the single burner experiments is to:

1. determine the effect of burner parameters for a variety of fuels;
2. evaluate modifications of burner design concepts for performance optimization; and
3. establish the effect of burner scale-up on emission performance as a function of fuel type.

Since large quantities of some coals that were tested in the screening studies were already available on site, several of those coals were tested at the larger scales in the SWS and LWS facilities. This was accomplished to obtain an early indication of potential operational problems that might be encountered, to compare the results with the small-scale results, and lastly, generate some performance data that could be applid to design modifications.

The three coals available at EER were the baseline Utah coal (No. D) and two coals used in other EPA studies (Nos. A and C). Both coals C and D were studied in the small-scale reactor. The compositions of the coals were given in Table 4-6 on an as-received basis. The studies have been carried out with the double concentric burners previously shown in Figure 5-1 at two design firing rates of 12.5 and 100 x 10^6 Btu/hr. Since both burner scales employ similar distribution of tangential velocity and similar locations for the outboard staged air injectors as well as burner exit half angles, this should allow a straightforward interpretation of the results.

For the 12.5 MBtu/hr burner two series of experiments were conducted. In the first series the tests were conducted over a range in excess air, keeping the primary zone stoichiometry constant at 0.6, and in the second series over a range in primary zone keeping the overall excess air at 4.2 percent O_2. The results showing the NO_x characteristics for the three coals are presented in Figure 6-12. When overall excess air was varied from about 2 to 9 the NO_x characteristics of the three fuels varied in a similar manner, increasing with increasing percent O_2. Further, as would be expected, the higher nitrogen-containing fuel resulted in the greatest emission levels while the lower nitrogen Utah coal gave the lowest emission levels. The results obtained under varying primary stoichiometry (SR_p) are somewhat more interesting in that at high values of SR_p the TRW No. 3 coal resulted in greater NO_x emissions that the TRW No. 2 coal. Further, at the lowest value of SR_p (~0.4) all three coals gave similar NO_x emissions.

F 6-12

The results obtained with the 100 MBtu/hr burner for the Utah and the TRW No. 2 coals are presented in Figure 6-13. It can be seen by comparison of the results in Figure 6-13 that the performance of the low NO_x burner is dependent upon fuel type and that there are considerable differences in the emission characteristics for the same burner with different fuels. These differences are not necessarily associated with overall nitrogen content since under highly staged conditions, emissions from the three coals are comparable. The results obtained at 100 x 10^6 Btu/hr compared to that for 12.5 x 10^6 Btu/hr suggest that the effect of fuel type of also associated with scale. For example, at the smaller scale the Utah coal gives a lower value of NO_x than the TRW No. 2 coal. This characteristic is reversed at the larger scale.

F 6-13

6.1.2 Combined NO_x/SO_x Burner Feasibility Experiments

A series of preliminary exploratory investigations were carried out in the small watertube simulator with the 12.5 x 10^6 Btu/hr low NO_x burner. The objective of these preliminary studies was to assess

1. The effect of sorbent type, (calcium and sodium compounds were used);

Stoichiometry of Coal Plus Primary Air = 0.25
Primary Air Swirl Angle = 45^0
Secondary Air Swirl Angle = 60^0

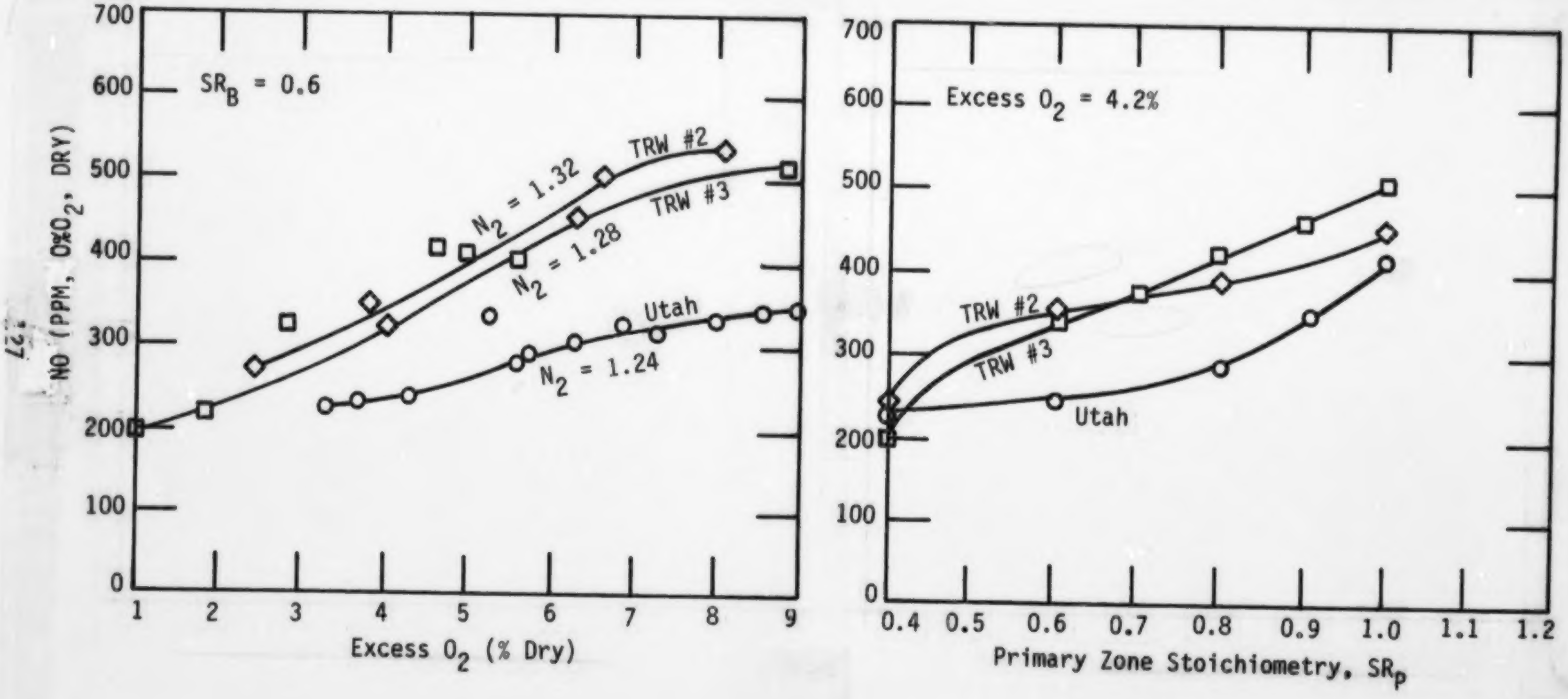
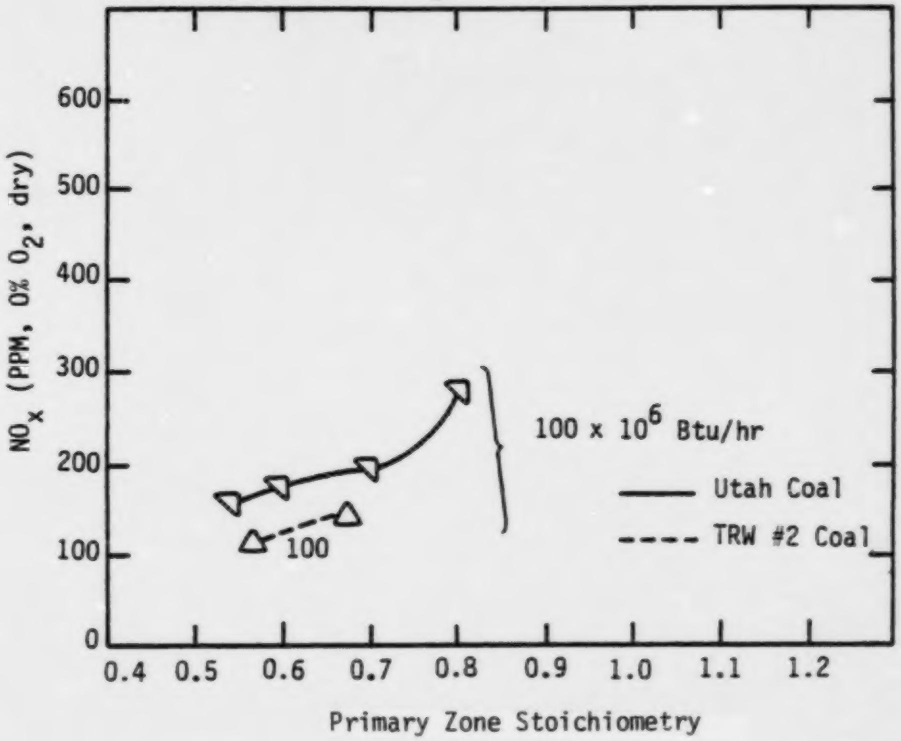


Figure 6-12. Fuels Performance with the 12.5M Btu/hr Double Concentric Burner Design.



Stoichiometry of Coal plus Primary Air = 0.25

Overall excess air = 4.2%

Primary Air Swirl Angle = 45°

Secondary Air Swirl Angle = 60°

Figure 6-13. NO_x Emissions for the 150 M Btu/hr Burner Using Two Differing Coals.

2. Sorbent ratio and coal type upon sulfur capture;
3. Determine whether there were significant advantages of operating under low NO_x conditions; and
4. Determine whether or not sulfur capture influenced NO_x emissions.

It is important to note that the low NO_x burner design is such that even under nonstaging conditions the coal/air mixing profile still provides for a slow-mixing central core. Consequently, even though unstaged the flame characteristics are quite different from those produced with current commercial turbulent burner designs. In addition, preliminary tests were also carried out using the Utah coal in the small refractory tunnel furnace to assess the effect of sorbent dispersion, flame temperature, the method of fuel/air contacting, and the combustion air staging upon sulfur capture. These latter experiments were designed to support the above-mentioned burner effort.

Pilot-Scale Burner Study

Sorbent Type and Ratio. Based on the previous studies, two basic types of sorbents appeared to have potential for high sulfur removal provided the optimum process requirements were provided. These are limestone and sodium bicarbonate. Although other stones such as dolomite and aragonite can provide higher removal efficiencies at Ca/S=1.0, high-purity limestone provides maximum SO_2 removal efficiencies with minimum lb-limestone/lb-sulfur in coal. Sodium bicarbonate (or more generally sodium compounds containing hydrogen and CO_3) appears to offer increased BET surface when injected into a high temperature environment due to communication. Table 6-1 lists the various sorbents studied in these preliminary investigations

T 6-1
[illegible]

Tests were first run without sorbent to determine the baseline operation and then with sorbent. For each case the sorbents were mixed with the coal prior to being fed to the pulverizer, then pulverized together. The sorbent was preground so that little additional size reduction could be anticipated. However, this was not measured in these tests. The coal/sorbent/transport air were then fed directly to the central burner tube and finally mixed with the combustion air beginning at the burner

Table 6-1. Sorbents Used in Sulfur Capture Tests

Limestone (Vicron)	$CaCO_3$>98.5% Size < 15 μm	Calcination and sulfation of limestones studied extensively
Trona	$Na_3H(CO_3)_2 \cdot 2H_2O$	Sodium-based sorbent
Sodium Bicarbonate	$NaHCO_3$ > 99.7%	Sodium-based sorbent
Phosphate Rock	Phosphorous ≈ 18% Calcium ≈ 33% Flourine ≈ .2%	
Bentonite	S_iO_2 ≈ 60% Al_2O_3 ≈ 20%	
Montmorellonite	Not analyzed	

throat location. Tests with and without sorbents were conducted over a range of excess air from about 1 to 9 percent excess O_2. The objectives of these tests were to obtain a preliminary indication of the effectiveness of each sorbent in removing SO_2.

Figures 6-14 through 6-21 provide a summary of the results obtained in the preliminary studies of the effect of sorbent type on SO_2 emissions. Data are presented showing SO_2 emissions as a function of excess air for the coal with and without additive, staged and unstaged. Emissions without additive indicate inherent sulfur capture of between 5 and 10 percent.

For the purposes of this report and because of the preliminary nature of the results, the sulfur reductions quoted in Table 6-2 are based upon the highest SO_2 emissions. Percentage SO_2 reduction is defined by

$$SO_2 \text{ \% Reduction} = \frac{SO_{2_{coal}} - SO_{2_{coal + sorbent}}}{SO_{2_{coal}}} \text{ @ 0\% excess } O_2$$

The limestone results are very encouraging in that the results suggest that the entire BET surface of the sorbent can be utilized when injected with the coal under controlled fuel/air mixing conditions. The sodium-based

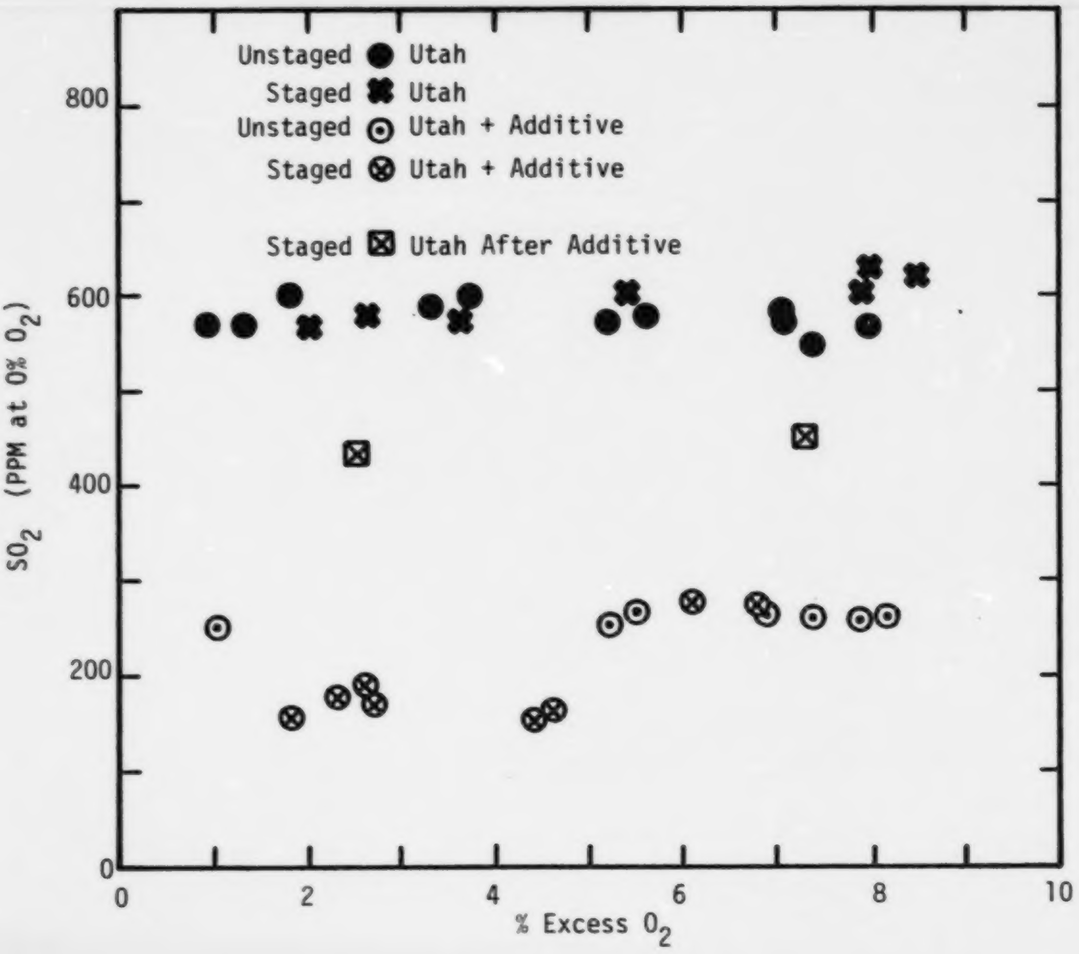


Figure 6-14. The Effect of Limestone Addition on Sulfur Oxide Emissions from the Utah Coal (Ca/S = 1).

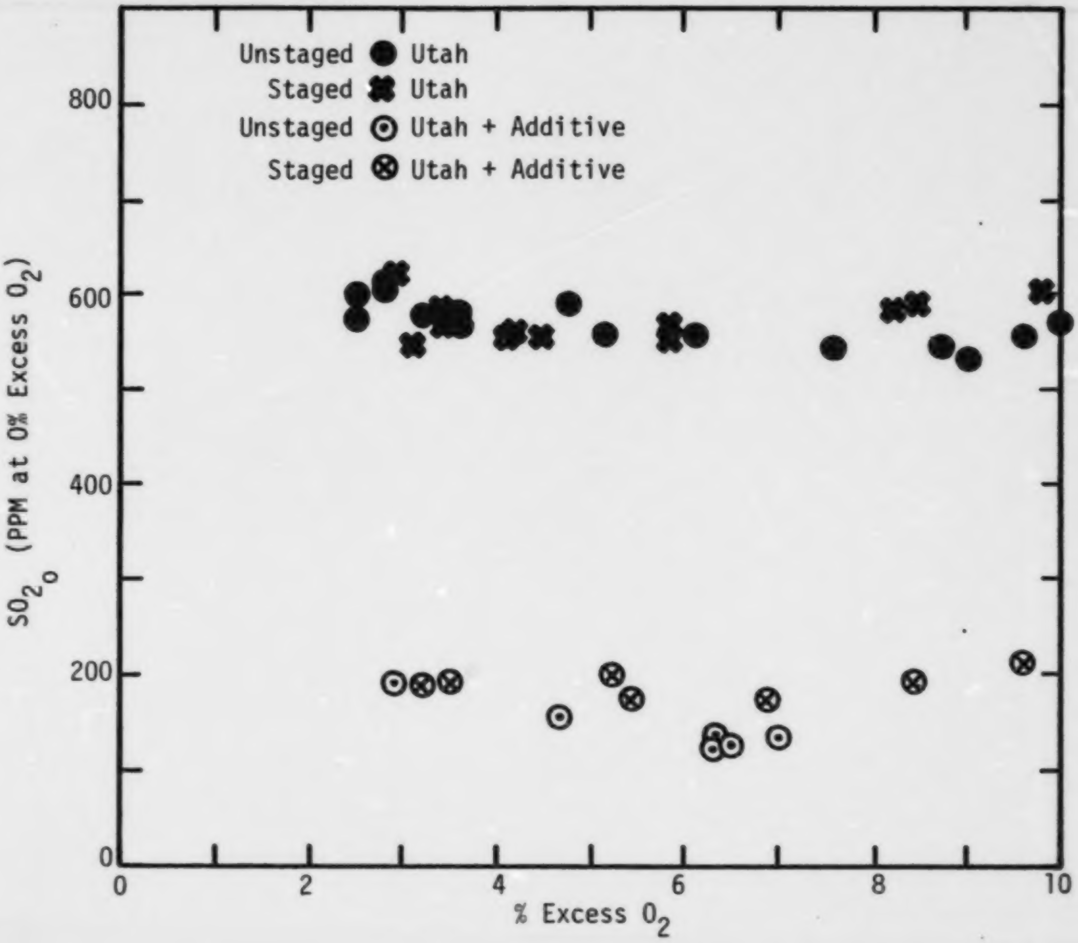


Figure 6-15. The Effect of Limestone Addition on Sulfur Oxide Emissions from the Utah Coal (Ca/S = 2).

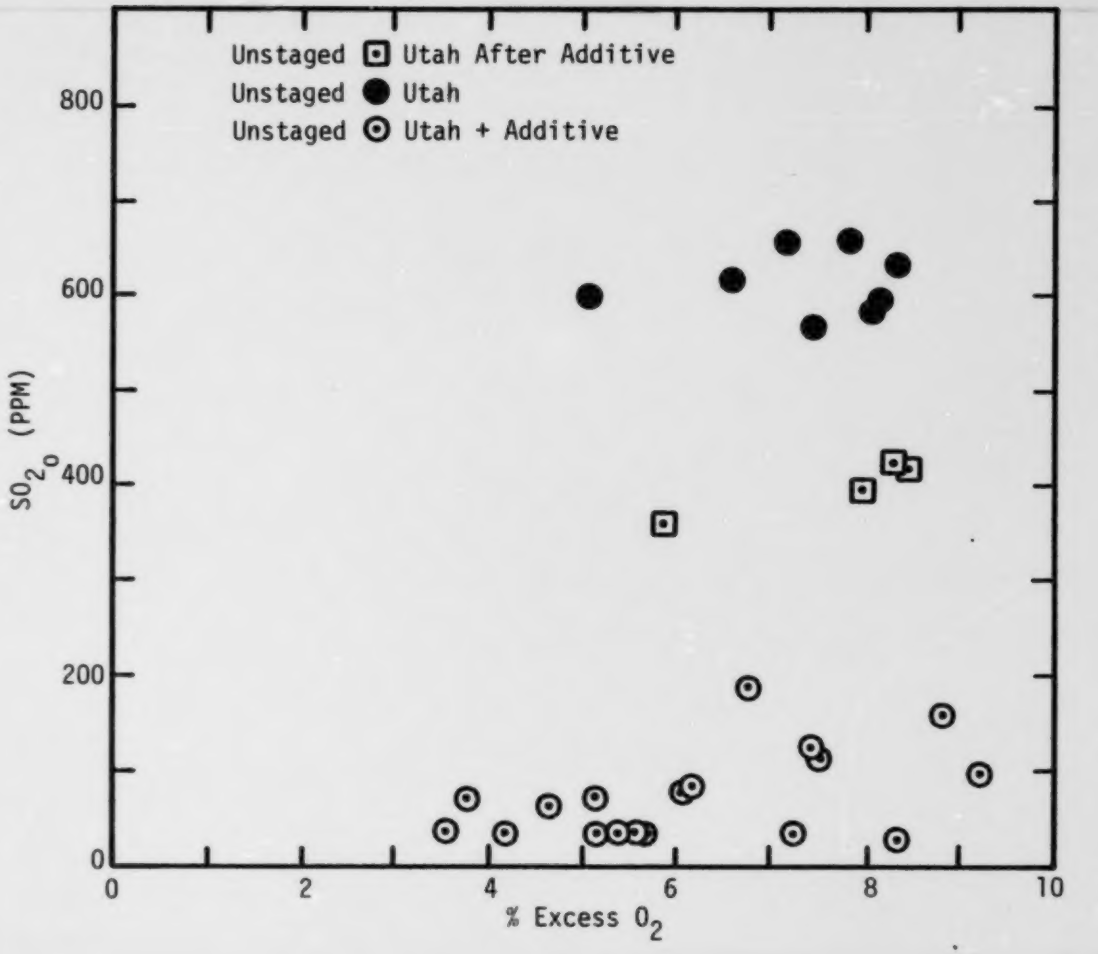


Figure 6-16. The Effect of Limestone Addition on Sulfur Oxide Emissions from the Utah Coal (Ca/S = 3).

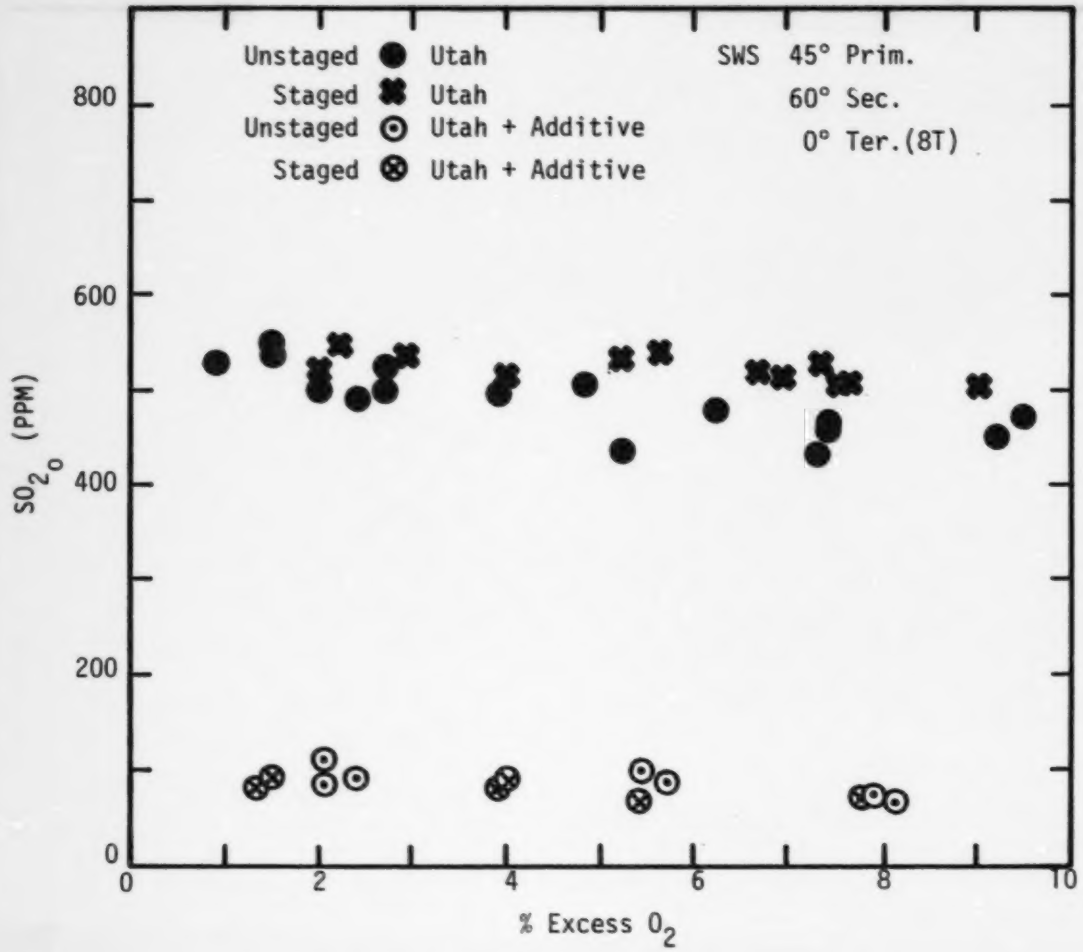


Figure 6-17. The Effect of Trona Addition on Sulfur Oxide Emissions from the Utah Coal (Na/S = 4).

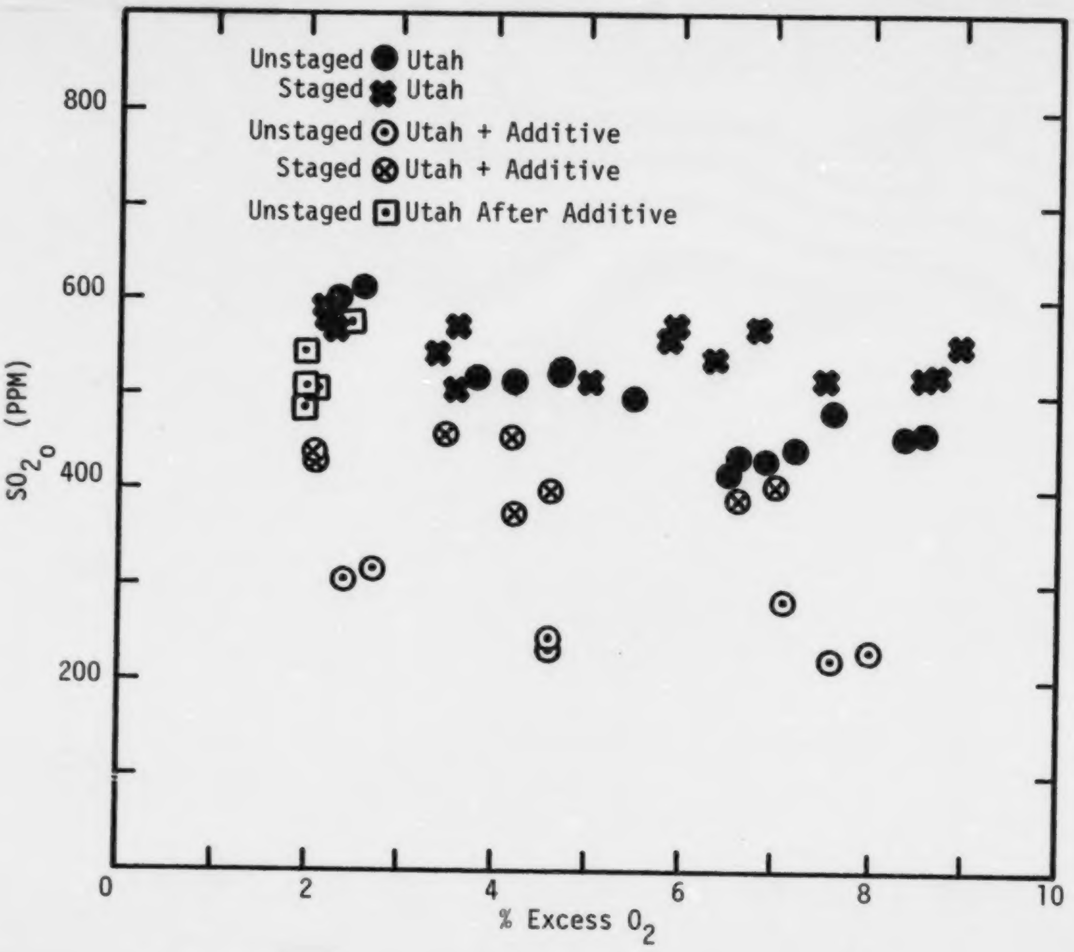


Figure 6-18. The Effect of Sodium Bicarbonate Addition on Sulfur Oxide Emissions from the Utah Coal (Na/S=2).

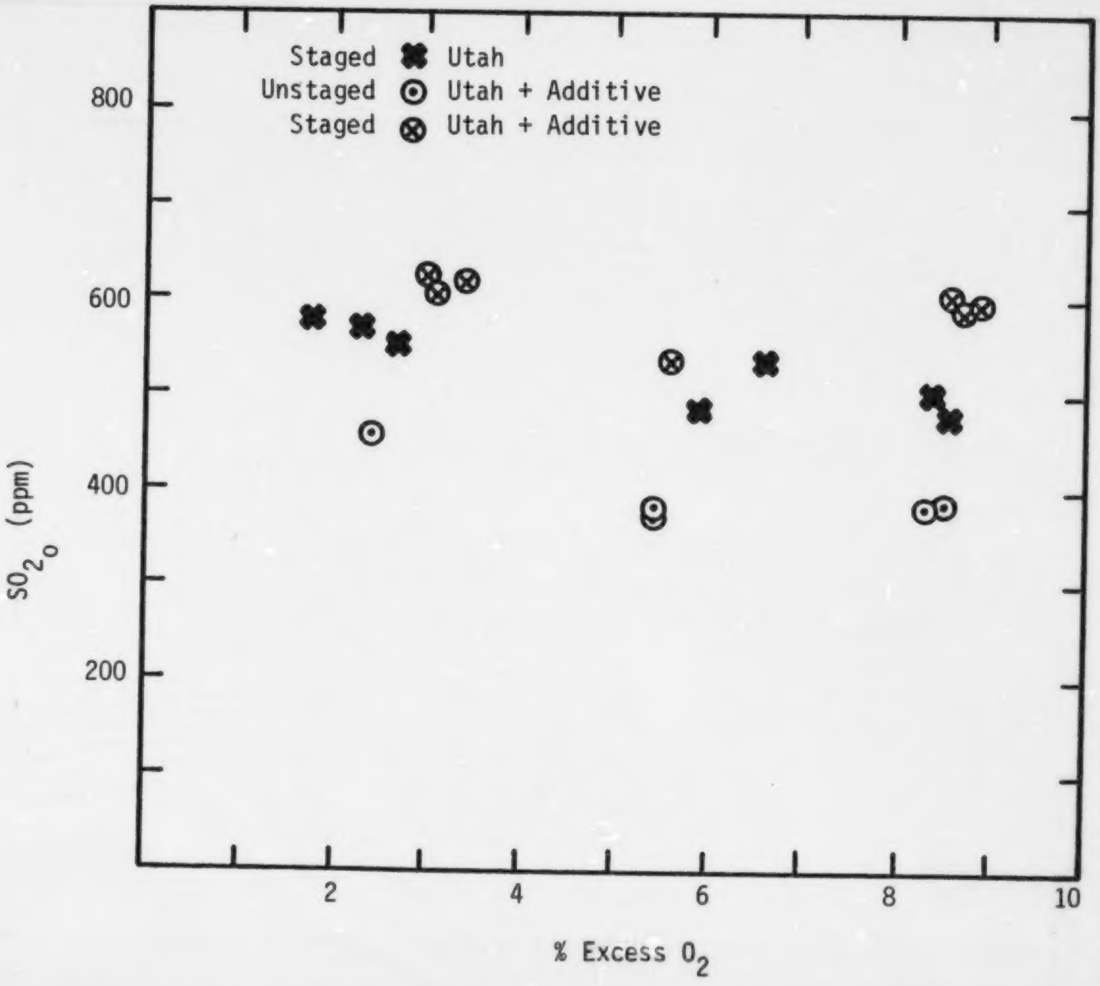


Figure 6-19. The Effect of Phosphate Rock Additive on Sulfur Oxide Emissions from Utah Coal.

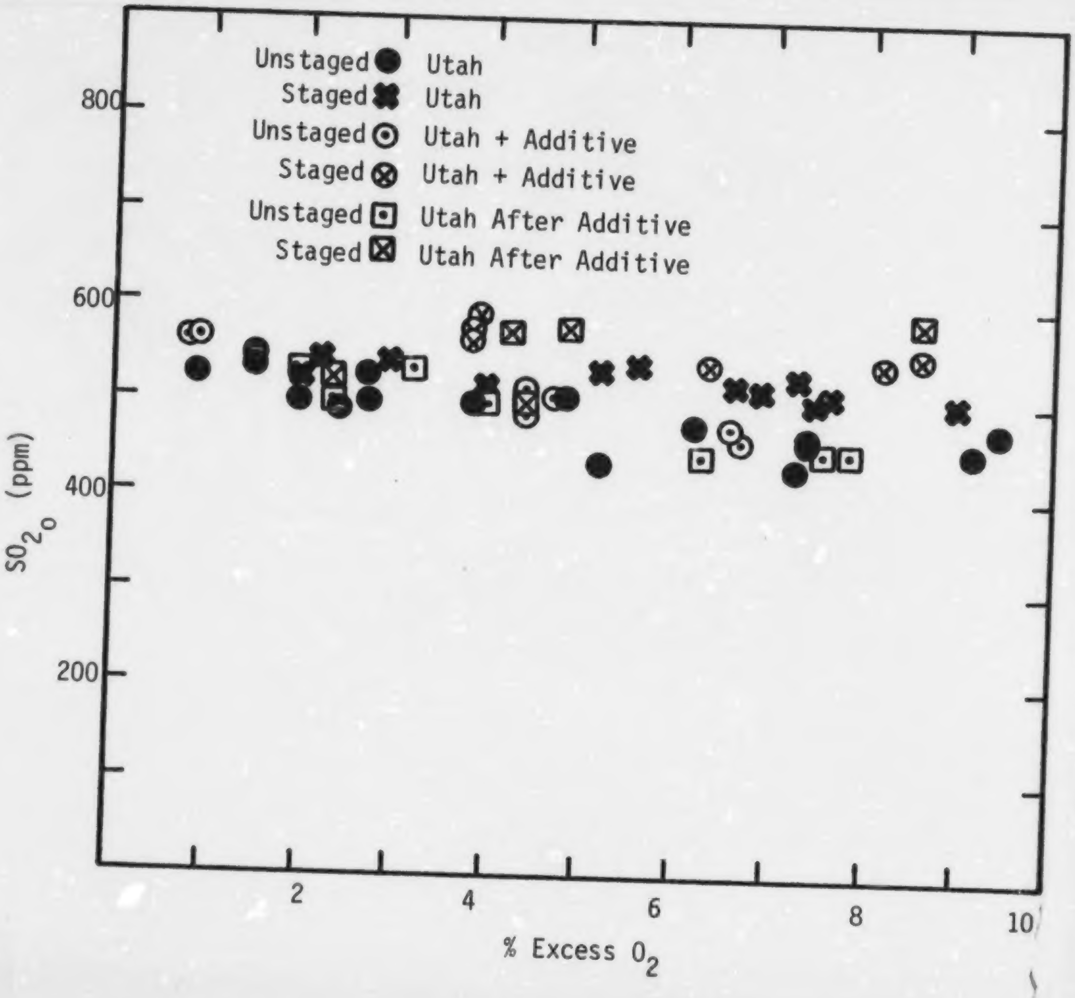


Figure 6-20. The Effect of Bentonite Additive on Sulfur Oxide Emissions from Utah Coal.

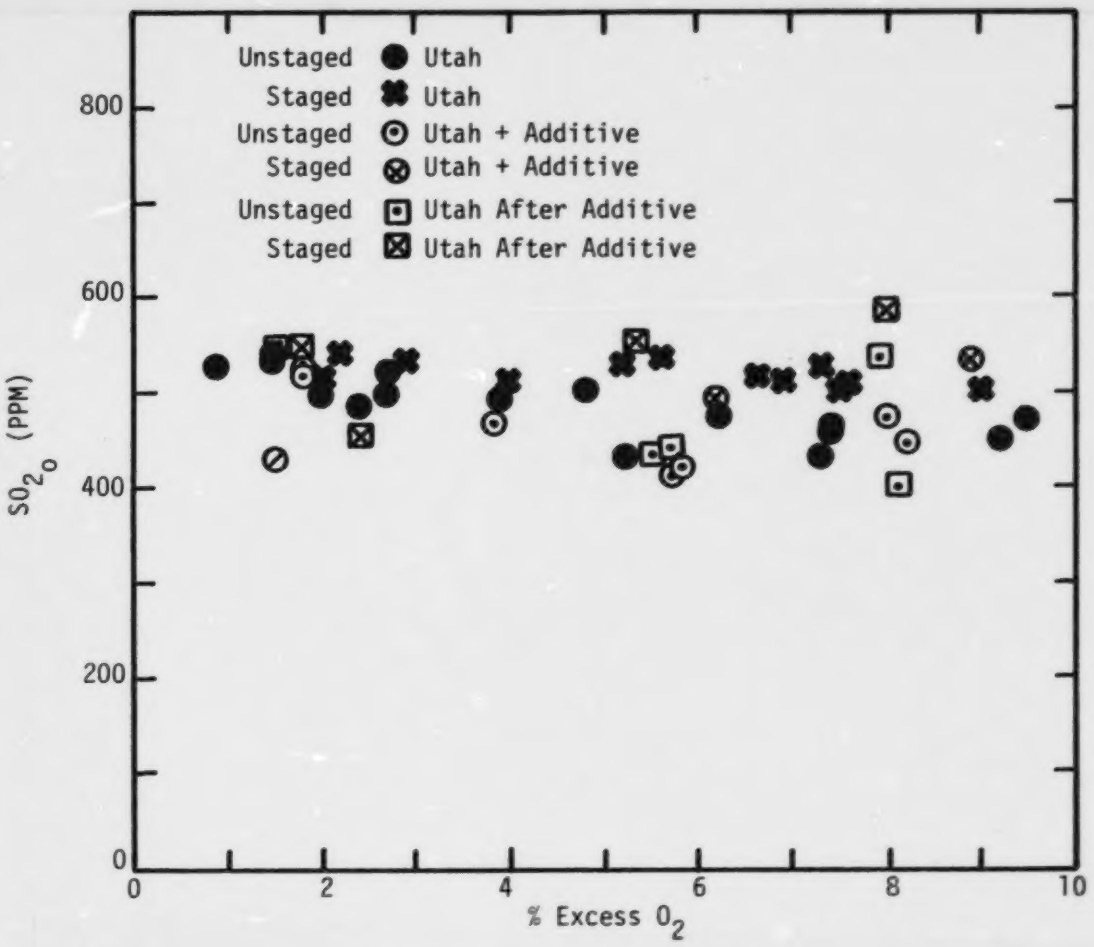


Figure 6-21. The Effect of Montmorillonite Addition on Sulfur Oxide Emissions from Utah Coal.

sorbents did not appear to offer any advantages over the calcium-based stone so they were not evaluated further. For the limestone, increasing the Ca/S ratio showed an increase in SO_2 reduction roughly in the same proportions as other investigators have found.

Table 6-2. Summary of Results

Coal	Sorbent	$Ca/_{S=1}$	$Ca/_{S=2}$	$Ca/_{S=3}$	$Na/_{S=2}$	$Na/_{S=4}$
Utah (Low Sulfur)	Limestone	50	70	80		
	Trona				40	80
	Sodium Bicarbonate				50	

Coal Type. Experiments were also conducted with a high sulfur coal in the same manner as for the Utah coal. The results are presented in Figure 6-22. Note that the SO_2 levels are considerably higher for this coal than for the Utah coal (see Figure 6-14) which, of course, is reflective of the high sulfur values in the TRW No. 3 coal. The baseline values of SO_2 are about 3000 ppm which is about 90 percent conversion of the sulfur into the gas phase. Injection of limestone again reduced the SO_2 levels in the flue gas and the same band of SO_2 levels were observed regardless of whether the burner was operating staged or unstaged.

Burner/Furnace Conditions. The data presented in Figures 6-14 through 6-22 gives no indication that operation under staged conditions consistently improves sulfur capture. However, it should be noted that NO attempt was made to optimize burner variables during the sorbent tests. Figure 6-23 presents NO_x data staged and unstaged, with and without limestone addition. It can be seen that the presence of the sorbent had no effect upon NO_x emissions.

The ultimate value of sorbent injection with the pulverized coal as a means of reducing SO_x emissions will depend upon whether the conditions encountered in the SWS in these preliminary studies can be found in operating boilers. The tests were carried out at between 50 and 75% full load (because of batch mixing) and the furnace is not fitted with a convective section. Even though the furnace is part refractory, the combustion

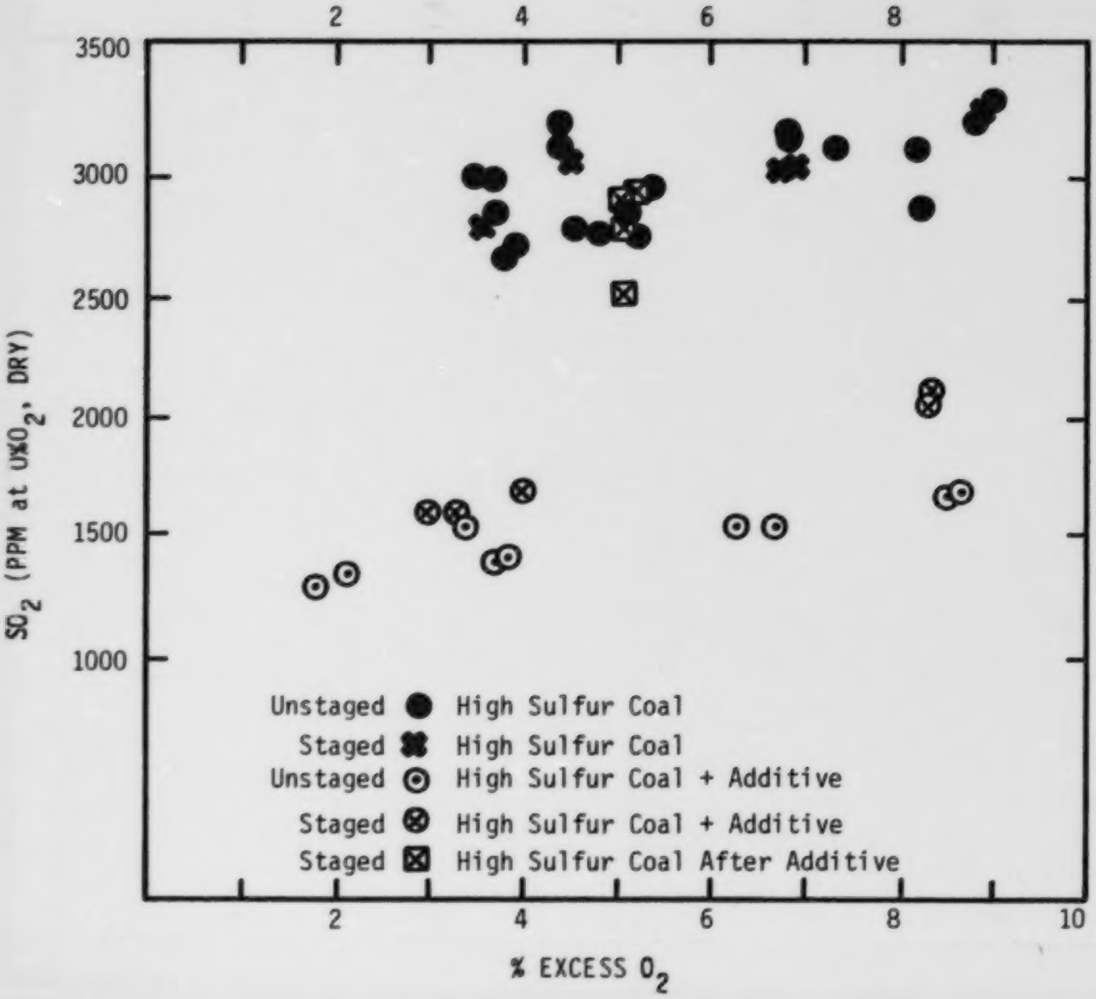


Figure 6-22. The Effect of Limestone Addition on Sulfur Oxide Emissions From a High Sulfur Coal (Ca/S = 1).

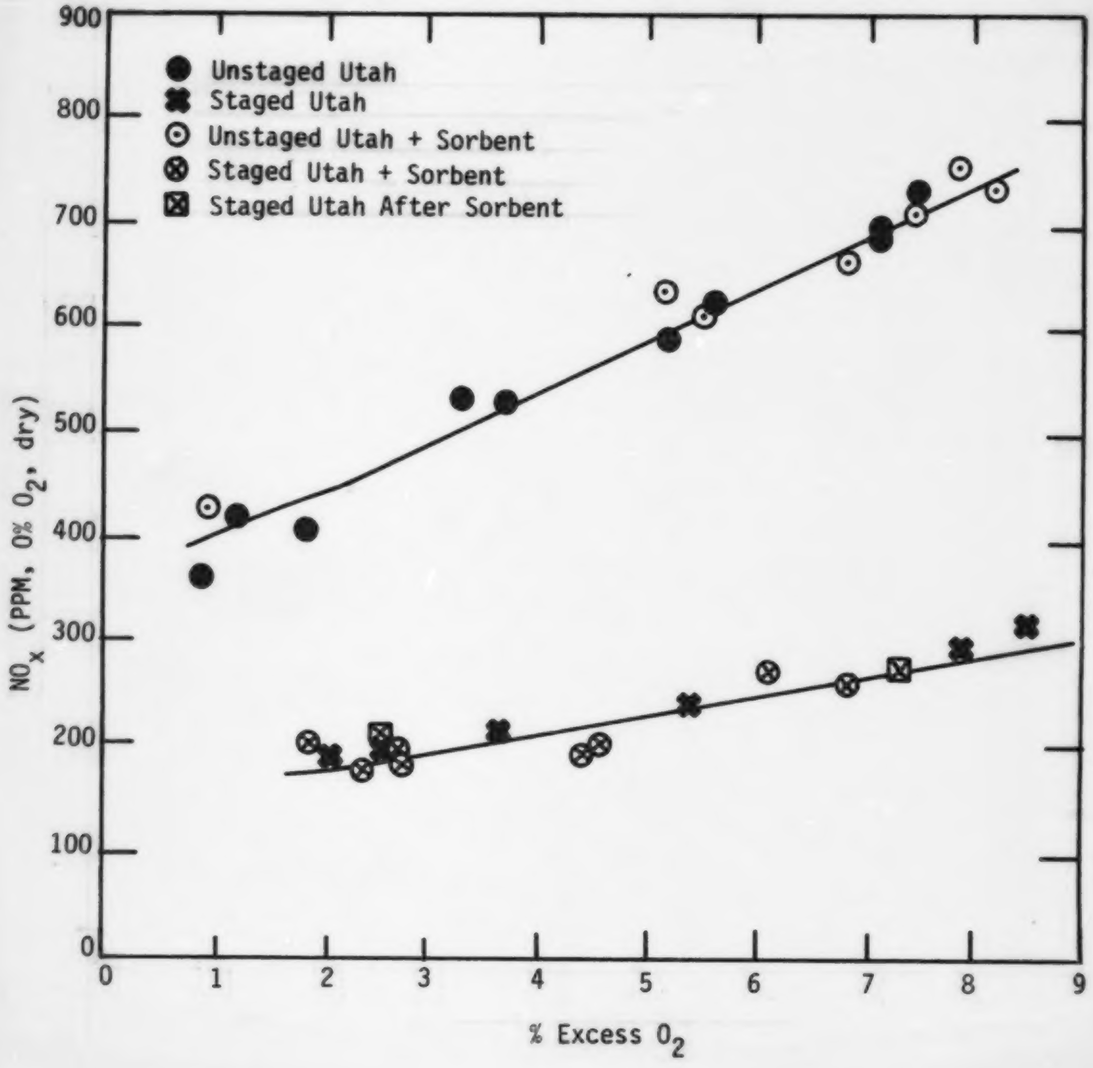


Figure 6-23. The Effect of Sorbent on NO_x Emissions (Utah Coal Ca/S = 1).

products will probably be quenched faster than in an operating boiler.

After the tests had been run for many hours, the furnace contained deposits which were still active; accounting for some of the data scatter and the time needed to attain baseline after sorbent injection. This effect is difficult to translate into operating terms.

Rapid Screening in Small-Scale Furnace

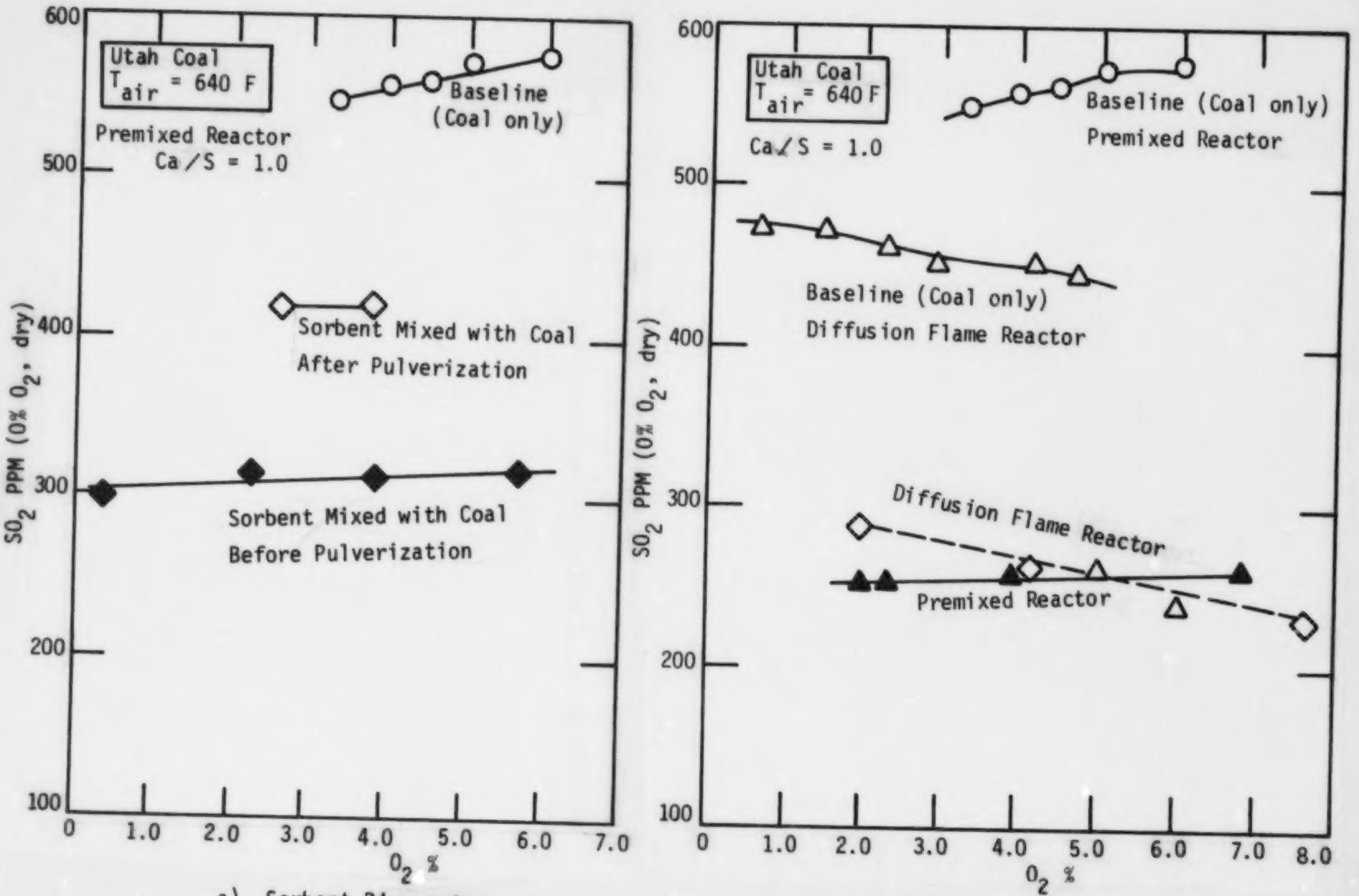
Method of Dispersing Sorbent in Coal. The proposed use of dry sorbents for SO_2 control requires that the sorbent be injected into the burner with the coal. The easiest way of accomplishing this with a minimum of additional hardware is to add the sorbent to the coal as it enters the pulverizer, thereby utilizing the existing coal delivery systems. It should be noted, however, that the actual method employed (e.g., combine with coal in pulverizer, in-line mixing after pulverizer) will probably depend on the specific pulverizer capacity at the site. Since the selected technique for addition of the sorbent to the coal will require some mixing process, an assessment was made of the sensitivity of the overall SO_2 capture process to the input sorbent uniformity. The two limiting cases mentioned above were investigated by:

- *Pulverization with the coal*. The finely ground sorbent was mixed with the unpulverized coal, put into the pulverizer where the coal was pulverized. The resulting mixture was then put into the feed hopper and fed to the reactor.
- *Mixed after pulverization*. The coal was pulverized separately and then mixed with the ground sorbent; tumbled in a separate drum to ensure reasonable mixing then put into the feed hopper. The resulting mixture was then fed to the reactor.

These two approaches should produce differing sorbent/coal distributions since attainment of uniform mixing after pulverization requires extensive tumbling. Mixing during pulverization results in uniform input to the delivery system and immediate feeding to the reactor. Consequently, mixing before pulverization should produce more uniform distribution of the sorbent and coal than would mixing after pulverization.

In order to define the effect of sorbent uniformity on SO_2 removal, it is important to ensure that the input nonuniformities in sorbent/coal are maintained throughout the reactor mixing process, that the temperature time characteristics are identical in the two experiments, and that the coal and air distribution in the reactor are uniform. These requirements are met with the premixed reactor described above wherein the mixture uniformity is controlled by the impinging jet dynamics and coal/sorbent input conditions. Further, with impinging jets it is well-known that the mixing of the injectants (coal/sorbent/transport air with the combustion air) will be accomplished rapidly. Also, the plug flow nature of the reactor design assures that the subsequent reaction takes place under conditions dictated by the input characteristics rather than the chamber flow characteristics.

A brief series of experiments were conducted over a range of excess air levels using the Utah coal and limestone to determine if the method of mixing the sorbent with the coal would significantly change the SO_2 capture efficiency. The resulting influence in sulfur capture is shown in Figure 6-24. The upper curve (Figure 6-24a) is the baseline flue gas SO_2 levels F6-24 when injecting coal only and for the Utah coal these levels represent almost quantitative conversion of the sulfur in the coal to SO_2 (i.e., 642 ppm at 0 percent O_2, therefore very little sulfur is remaining with the ash). When the sorbent was mixed with the coal after pulverization a 23 percent reduction in SO_2 level occurred, and when mixed with the coal prior to pulverization a 44 percent reduction resulted. These results suggest that the dispersion of the limestone in the coal has a significant effect upon the efficiency of sulfur removal. Further, it appears more desirable to mix the sorbent with the coal prior to pulverization for maximum SO_2 removal. It is important to note that while these experiments show that sorbent mixing uniformity is important, detailed measurements as to the degree of uniformity were not made. Therefore, it is not known at this time whether the changes in uniformity produced were minor, showing extreme sensitivity to this variable or large, suggesting only minor sensitivity. Based on purely hueristic arguments, it would appear that the uniformity of the sorbent with the coal is an extremely important consideration in achievement of maximum SO_2 removal efficiencies.



a) Sorbent Dispersion

b) Fuel/Air Contacting

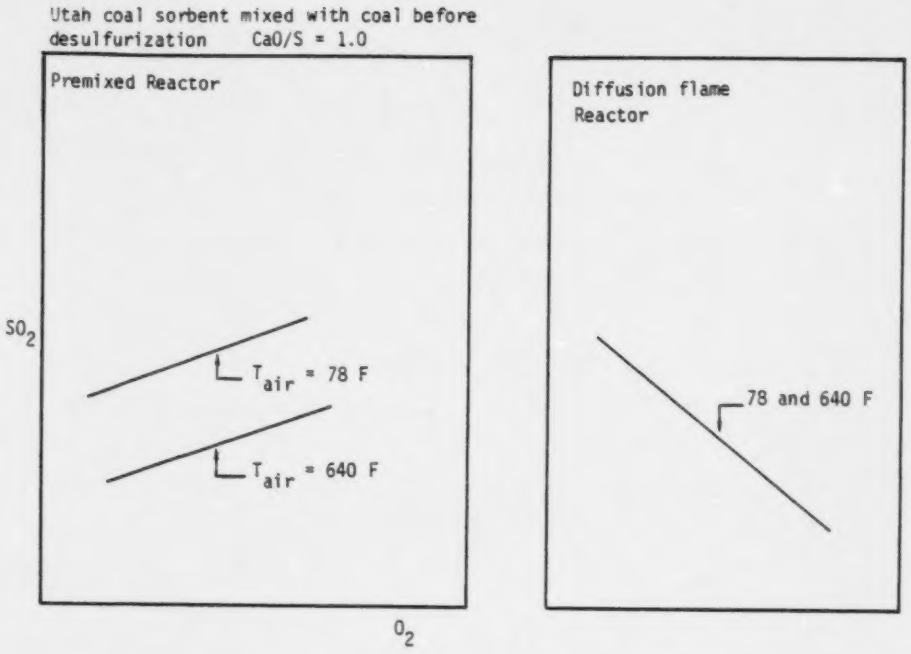
Figure 6-24. Effect of Sorbent Dispersion and Fuel/Air Contacting on SO_2 Reduction.

Variable Fuel/Air Contacting. Recent photographic results of the flame patterns from the low NO_x burner showed that low NO_x could be achieved with both a relatively long coherent diffusion-type flame or a moderately short flame with some internal recirculation. While the initial or near-field temperature time characteristics would not be altered, the far-field temperature time characteristics for these two flame types should experience some change. Based on the experiments presented above, this type of variation could change significantly the calcination/sulfation process.

Two cases were examined, a uniformly premixed reaction sequence and a diffusion-flame mixed-reaction sequence. The results presented in Figure 6-24a and b show that the reaction process can have a significant effect on the SO_2 removal. For the premixed reaction case increasing the excess air level had only a minor effect on the SO_2 removal, increasing with increasing O_2. However, for the diffusion flame (6-24b) SO_2 removal was considerably more sensitive to excess air levels (larger change in temperature time characteristics) and show a reduction in SO_2 level with increasing excess air; opposite to that for the premixed reactor.

Gaseous Environment. Successful operation of the low NO_x burner (for control) requires that the stoichiometry/residence time characteristics be optimized for maximum reduction of fuel nitrogen emissions. In addition, another variable available to the operator is the preheat temperature which' must be sufficiently high for good ignition characteristics and maximum overall plant efficiency. Some variation in this parameter is, however, possible. The effect of these three variables was briefly studied in the small-scale reactor.

The effect of combustion air preheat temperature on SO_2 removal is shown in Figure 6-25 for the two differing reactor schemes. For the premixed reactor, preheat temperature had a significant effect on SO_2 removal while almost no effect is seen for the diffusion flame reactor. These results could be attributed to the fact that peak temperatures in the diffusion flame are not as dependent upon air preheat temperature as are those in the premixed case.



IMPROVE AXIS LABELS

Figure 6-25. Effect of Air Preheat on SO_2 Reduction.

Staged conditions were accomplished by operating the reactor at one stoichiometry then injecting secondary air at a fixed location downstream. The gases were then allowed to flow to the flue stack where SO_2 measurements were made. The first-stage residence time was, therefore, defined by the gas velocity and position of secondary air injection. Keeping the first stage and second-stage residence time constant, the effects of reducing the primary stoichiometry from 0.6 to 0.8 are shown in Figure 6-26. Although there is some effect of primary-zone stoichiometry on sulfur capture, this data does not indicate an overwhelming impact. Unfortunately, changes in the primary zone stoichiometry also changes temperatures and residence times; therefore, the influence of gas phase stoichiometry on sulfur capture cannot be readily assessed.

Using the staged configuration, residence time was also varied by changing the location of secondary air injection. Two primary zone residence times were studied, 0.8 sec and 1.2 sec, at two primary stoichiometries. The results shown in Figure 6-26 reveal that increased primary residence time results in a reduction in SO_2 level of the flue gas.

Equilibrium Considerations

Equilibrium calculations were made to test the contention that sulfides are more stable at high temperatures than sulfates. If sulfides are formed and this is true, then significant sulfur capture may result at the high temperatures normally associated with pulverized coal combustion. Calculations were performed to evaluate the effects of temperature, stoichiometry, and sulfur concentration. Figure 6-27a shows that the equilibrium dissociation limit for $CaSO_4$ is around $1400^{o}K$. At slightly lower than theoretical air, the higher sulfur concentration provides a driving force to form more CaS than $CaSO_4$ at relatively low temperature as shown in Figure 6-27b. The low temperature formation limit is lower for $CaSO_4$ than CaS at appropriate air stoichiometries which would be beneficial under exhaust conditions. Figure 6-27b indicates that the temperature for sulfur capture might be extended to $1700^{o}K$ for a high sulfur coal under reducing conditions but not for the low sulfur coal. Figures 6-28 and 6-29 present the $CaCO_3 \longleftrightarrow CaO \longleftrightarrow CaS \longleftrightarrow CaSO_4$ variational paths for the low sulfur and high sulfur coals. Throughout the variations, the driving force of higher sulfur concentration for sulfur capture is noted. The physical nature of partially

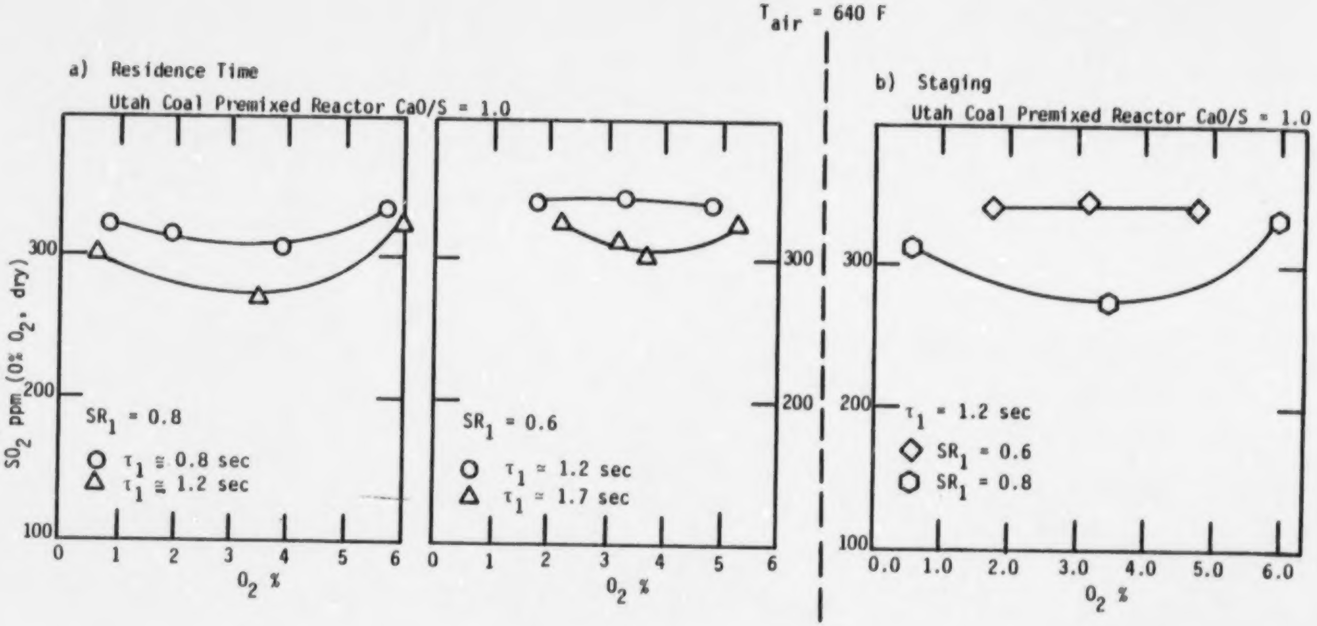
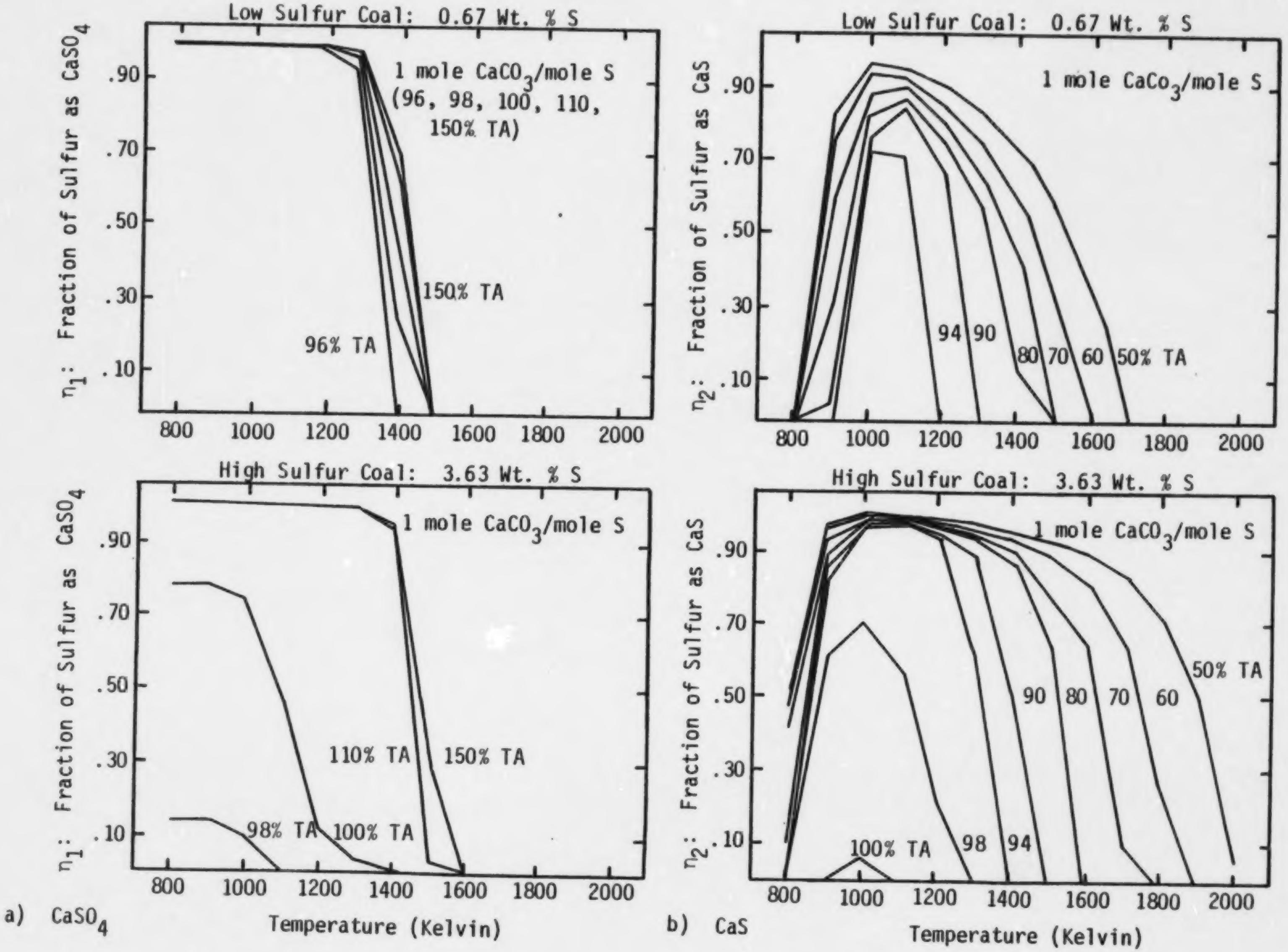
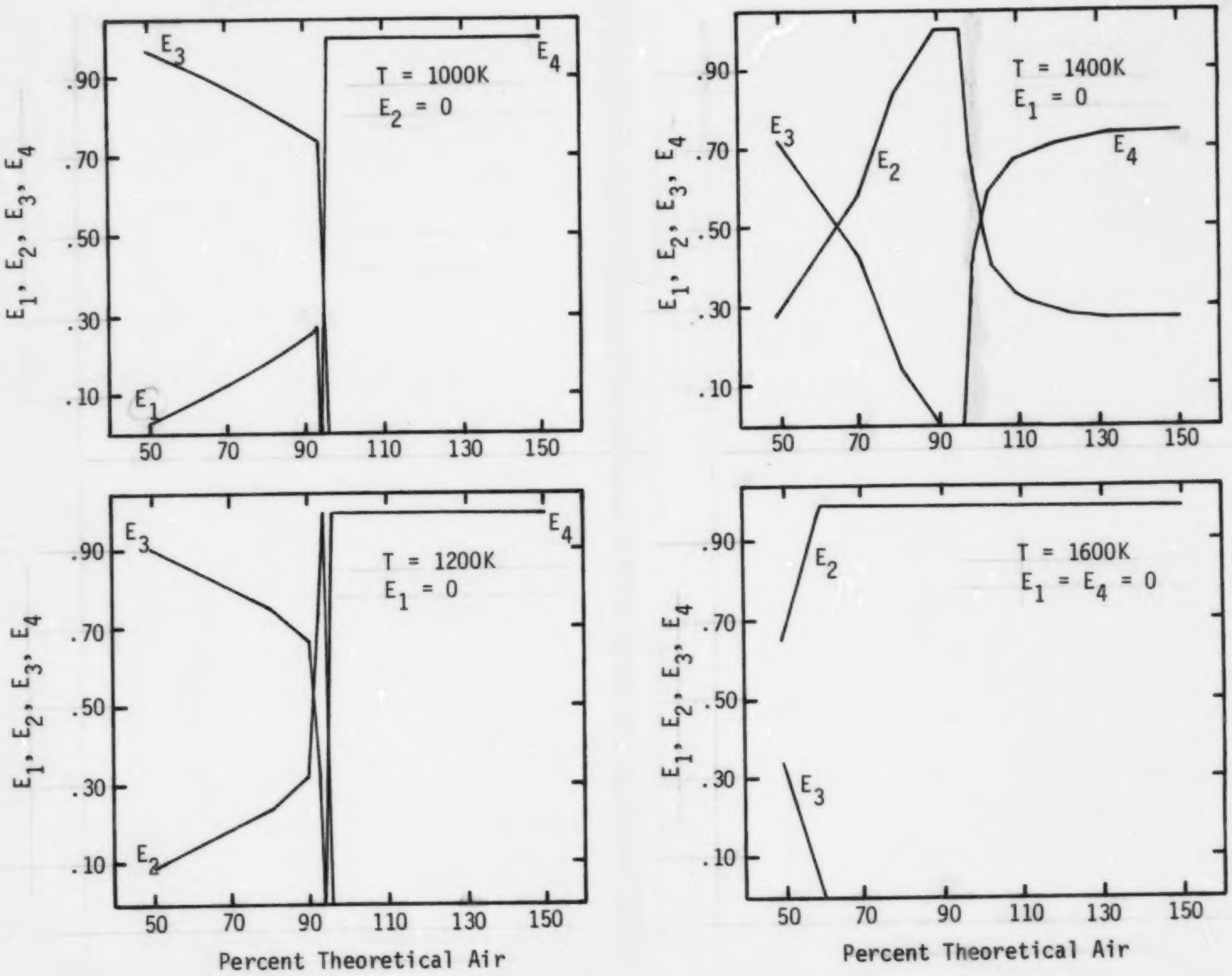


Figure 6-26. Effect of Residence Time and Staging on SO_2 Reduction.



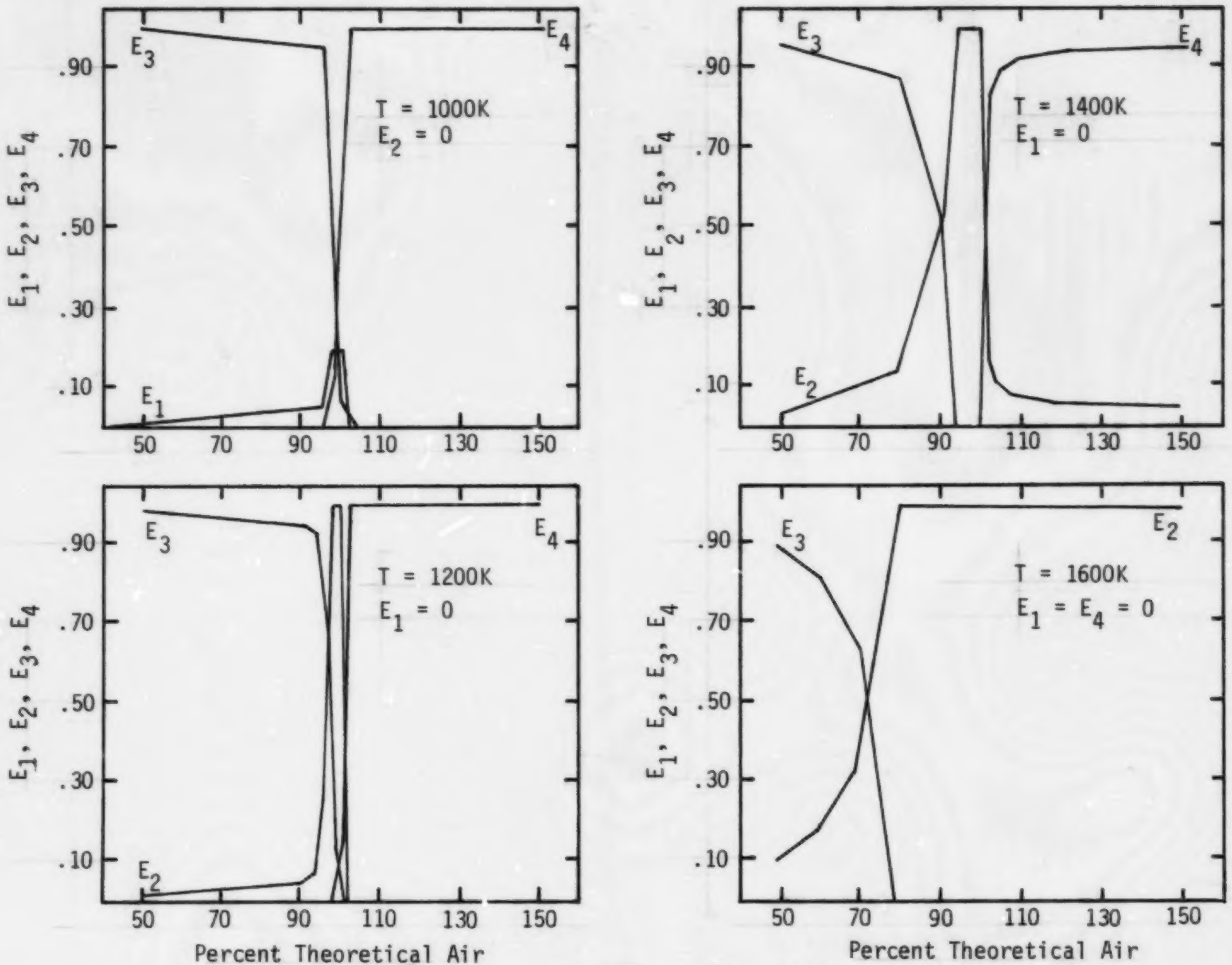
a) $CaSO_4$ b) CaS

Figure 6-27. Theoretical $CaSO_4$ and CaS Variation with Temperature and Stoichiometry.



E_1 = moles $CaCO_3$/total mole CaX
E_2 = moles CaO/total moles CaX
E_3 = moles CaS/total moles CaX
E_4 = moles $CaSO_4$/total moles CaX

Figure 6-28. Equilibrium Limestone Performance with Low Sulfur Coal.



E_3 = moles CaS/total moles CaX
E_4 = moles $CaSO_4$/total moles CaX
E_1 = moles $CaCO_3$/total moles CaX
E_2 = moles CaO/total Moles CaX

Figure 6-29. Equilibrium Limestone Performance with High Sulfur Coal.

reacted calcium oxide particles may actually prevent this effect. One noteworthy exception is seen by comparing the high and low sulfur coal results in Figures 6-29 and 6-30 at 1400^{o}K and 100 percent theoretical air. Significant sulfur capture occurs for the low sulfur coal and essentially zero capture for the high sulfur coal. Sulfur capture is known to be diffusion controlled over a large range of conditions, and the range near 100 percent theoretical air may be of concern. Figure 6-30 indicates that if all reactions are sufficiently quick to maintain an unfrozen equilibrium path then stoichiometry and temperature at the furnace inlet are not important (neglecting calcination and dead burning) since the postflame gas mixture is above theoretical air proportions, and therefore, a low enough temperature range should be maintained until quench.

The above equilibrium calculations do indeed show that CaS is more stable at higher temperatures than $CaSO_4$.

6.1.3 Burner Sensing and Control

The requirement for burner control systems to maintain optimum fuel and air distributions is being evaluated for the generalized low emission coal burner. As currently envisioned, the governing criteria for the control systems are: (1) the correlations of the minimum number of parameters which yield optimum low emissions performance; (2) safety which includes reliability; as well as (3) cost.

Microcomputer-based burner control systems have significant potential for improving current system performance, reliability and flexibility. Current burner control systems generally utilize discrete logic modules made of relays and/or solid state components. However, these systems have several features which are undesirable such as high costs associated with design, construction and changes in addition to off-line mode instrumentation which yields low reliability through late detection of hardware failures. Burner control systems also require a relatively large amount of space. Microprocessor technology can be utilized to reduce cost, increase reliability and minimize space. Therefore, the burner control systems being considered in this program are being based on interfacing with a microprocessor to provide on-line performance, safety detection and control.

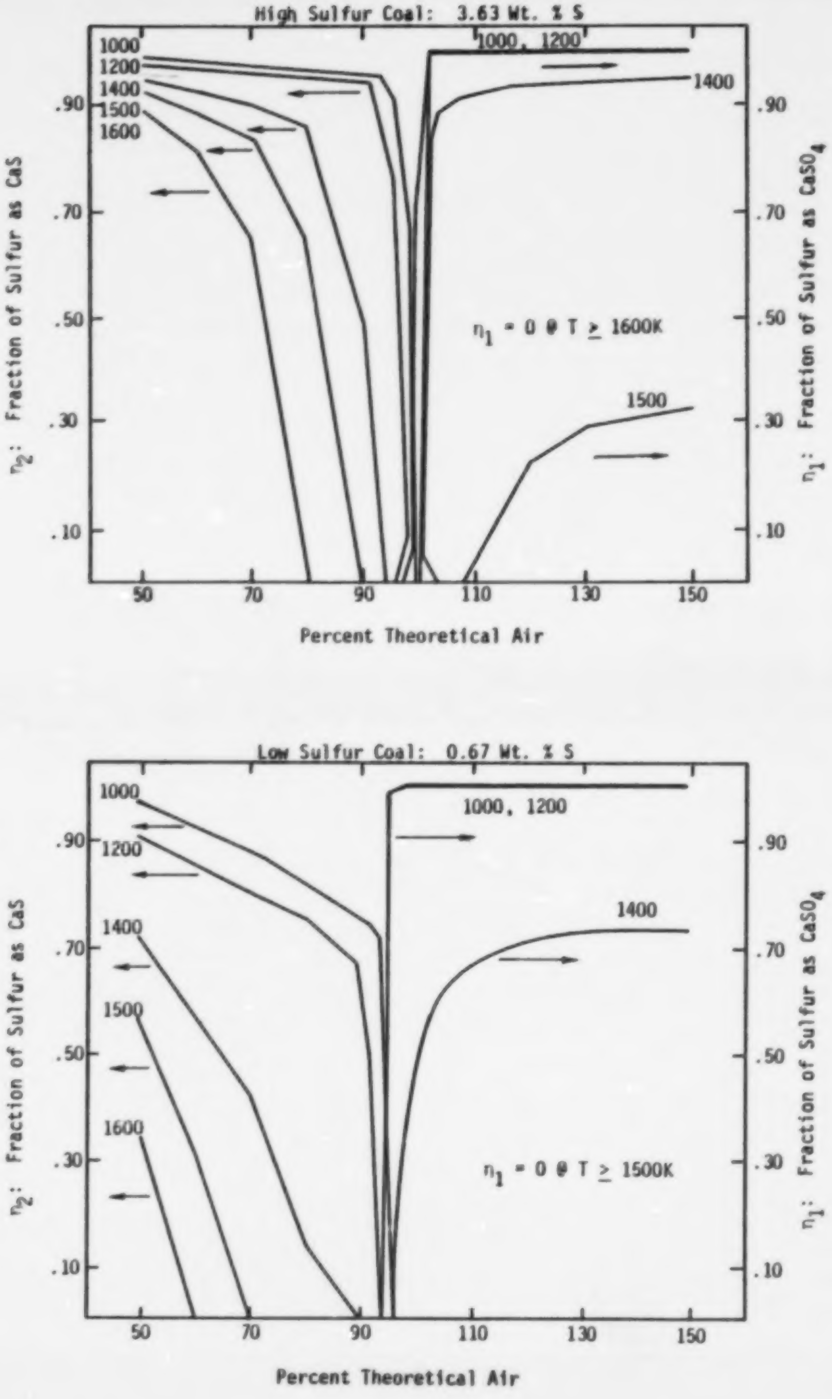


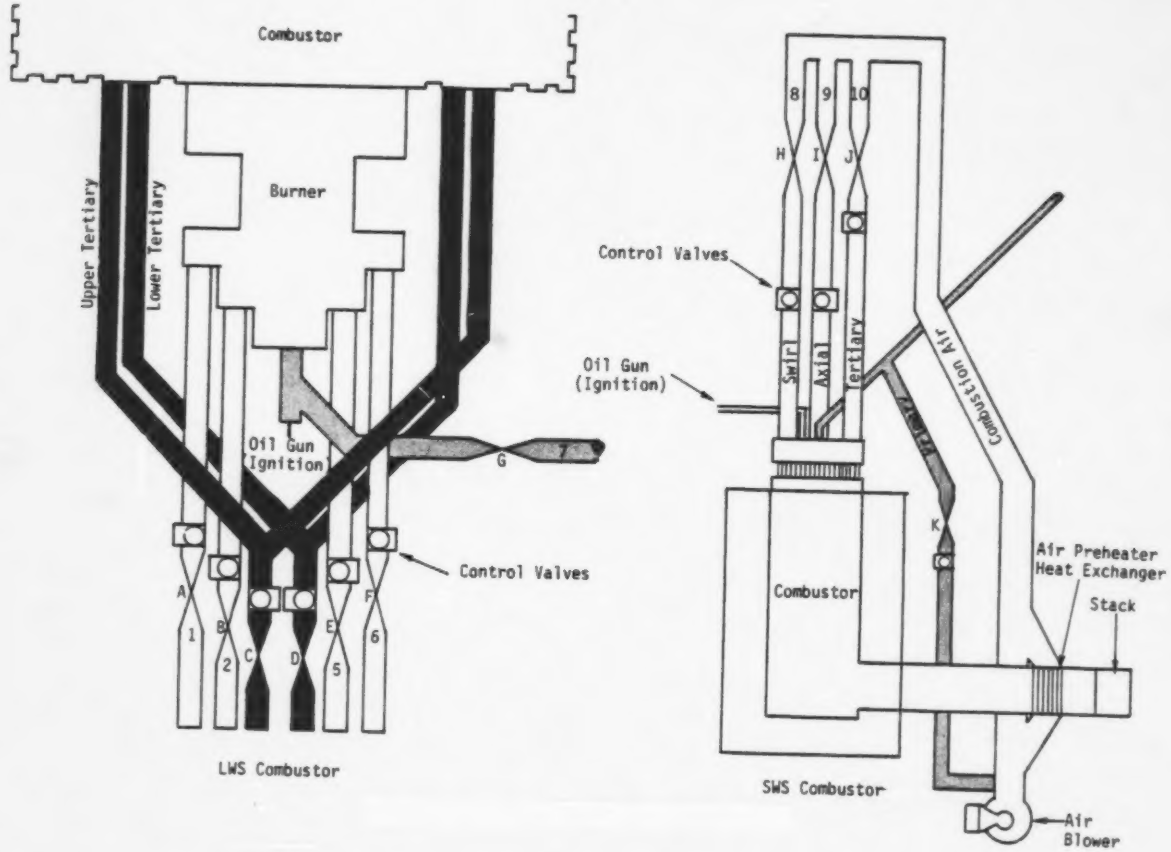
Figure 6-30. CaS/CaSO Equilibrium.

As the first step towards evaluation of prototype control system an HP desk computer (Model No.9825A) has been interfaced electronically with flow control valves. Sensors and feedback control devices have been implemented. The sensors consist of dynamic pressure transducers and thermocouples to characterize flows and hardware. The sensor signals go to signal conditioners, a Doric data logger, digital displays for manual operations and the HP computer which has been programmed to provide visual display of flow variables and hard copy output of reduced data. In this manner the burner, furnace and pulverizer performances are dynamically sensed, recorded, calculated and displayed. The nomenclature for the flow ducts, venturis and control valves for one set of burners in the SWS and LWS combustors is presented in Figure 6-31 and the flow control diagram is presented in Figure 6-32.

Performance data is being gathered and analyzed to evaluate the importance and influence of the multitude of parameters over a wide range. Some of the variables will be fixed and optimum combinations and ranges of the remaining variables will be determined for high efficiency, low emission operation. The variation of the optimum combination of the variables will be the basic input to the microprocessor of the burner control system. The optimum combinations of variables will be extended and refined as more generalized data becomes available. These data will form the basis of the automatic control transfer function. Currently, all control is done manually with switches. The sequential output of all reduced data, such as flow rate and emissions, is used as the guide for manual control. The two missing items for the automatic control systesm are: (1) the optimum combination of variables for the feedback transfer function software package; and (2) application of additional manipulating hardware as determined by the correlated variables.

6.1.4 Commercial Burner Studies

Commercial burners will be tested in the LWS facility to provide a point of reference for estimating the operating performance and define any potential problems that might be encountered with the low emissions burner concepts in field operations. Several commercial burner manufacturers (Table 6-3) were contacted to determine their willingness to



Combustor
Burner
Upper Tertiary
Lower Tertiary
Oil Gun
Ignition
G
7
Control Valves
A
B
C
D
E
F
1
2
5
6
8
9
10
H
I
J
K
Control Valves
Oil Gun
(Ignition)
Swirl
Axial
Tertiary
Combustion Air
Combustor
Air Preheater
Heat Exchanger
Stack
Air
Blower

LWS Combustor

SWS Combustor

Figure 6-31. Nomenclature for Combustors.

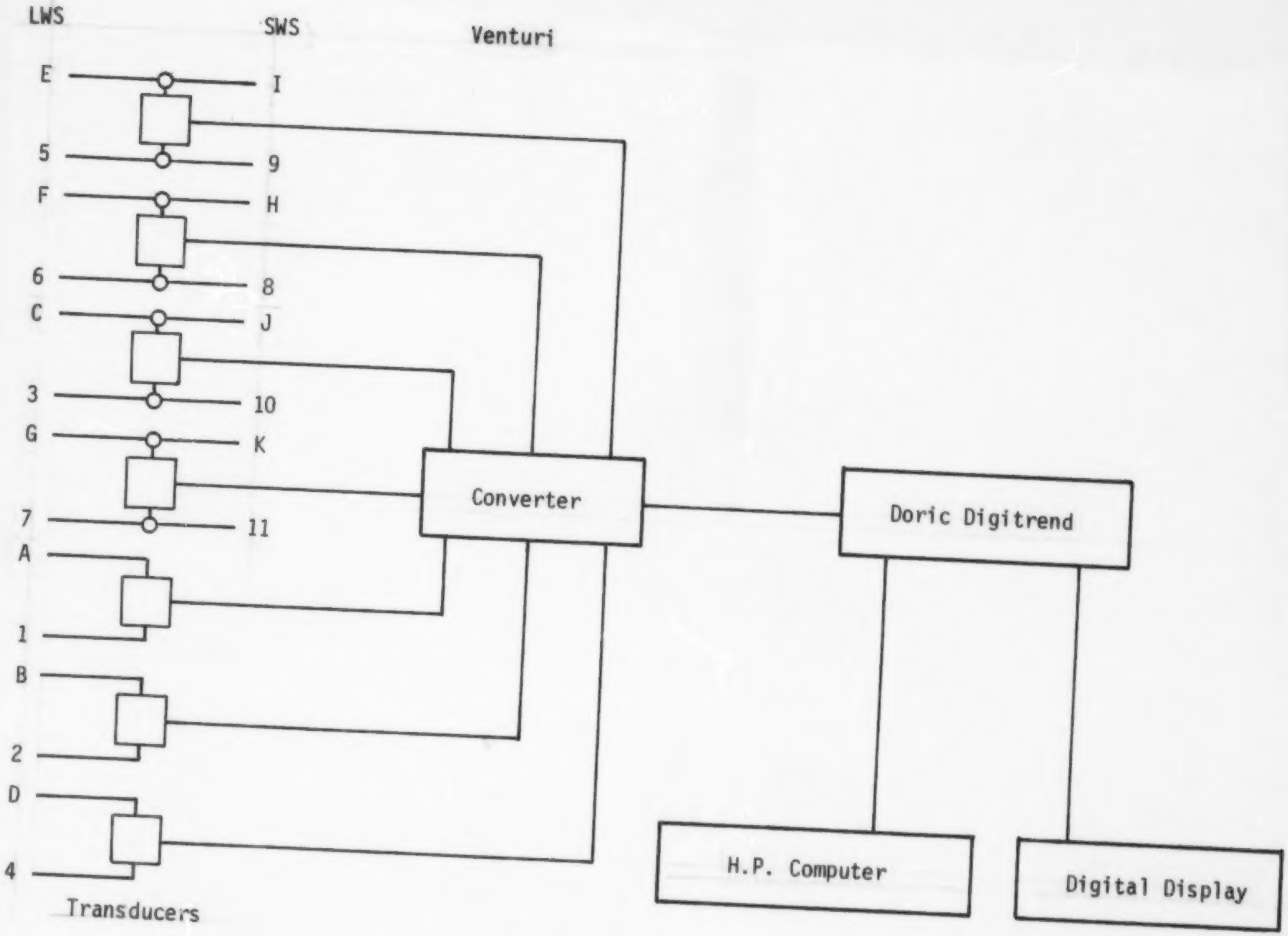

LWS
SWS
Venturi
E
I
5
9
F
H
6
8
C
J
3
10
G
K
7
11
A
1
B
2
D
4
Transducers
Converter
Doric Digitrend
H.P. Computer
Digital Display

Figure 6-32. Electronic Control Flow Diagram.

Table 6-3. Commercial Burners

		Evaluated		
Manufacturer	Company Burner Designation	Burner Size MBtu	"Boiler" Size	Available To This Program
Peabody	Dual Register	50-60	Full Range	Now
Coen	Dual Register	50	– –	No
Babcock & Wilcox	Dual Register	Full Range	90-700 MW	Now
	Advanced Duel Register	40	2 MW	Now
	Two-Stage (EPRI)			No
Foster Wheeler	Duel Register	35	40 MW	TBD
Steinmuller	IFRF	50		Now
CEA	Double Vortex	UK	– –	UK
Combustion Engr.	Tangential-Fired	Full Range	Ind. & Util.	UK
Riley Stoker	Turbo-fire	Full Range	Industrial	Will Discuss

UK - Unknown
TBD = To be determined

participate in this program and the availability of burners for testing. Due to the proprietary nature of many of the products and early stages of development of others, the positive responses were somewhat limited. Of those who were willing to participate, three were finally selected and will be tested in this program. These are:

1. Peabody Engineering Dual Register Burner
2. Steinmuller NO_x Staged Burner
3. Babcock and Wilcox Dual Register Burner

Schematics of each of these burners are shown in Figures 6-33, 34, and 35.

All burners have been received and the manufacturers are being contacted to assist in defining the test programs for evaluation of their burners. It is planned that all three burners will be tested consecutively in the LWS combustor at firing rates near the design point which, for the units available, is nominally 50×10^6 Btu/hr. The manufacturers' representatives will participate in installation, experimental definition of the design operational point and structuring of the test plan.

6.2 Discussion of Results

This report covers the first year's activities of a program designed to provide information which will allow the generalization and optimization of low emission coal burners. Since the data presented in the previous section represents only the initial results, more detailed discussions must await the acquisition of a complete set of data. Therefore, the conclusions reached to date must be considered speculative.

NO_x production in pulverized coal flames is the result of two different processes:

1. Thermal NO. This is produced by the fixation of molecular nitrogen, giving what is termed thermal NO because its rate of formation is strongly dependent upon temperature. There are two major mechanisms whereby thermal NO is produced. One of these is dependent upon the availability of oxygen atoms since the reaction $N_2 + O \rightarrow NO + N$ is the rate limiting step. The second mechanism involves the production of nitrogen-containing radicals by reactions of N_2 with hydrocarbon species.

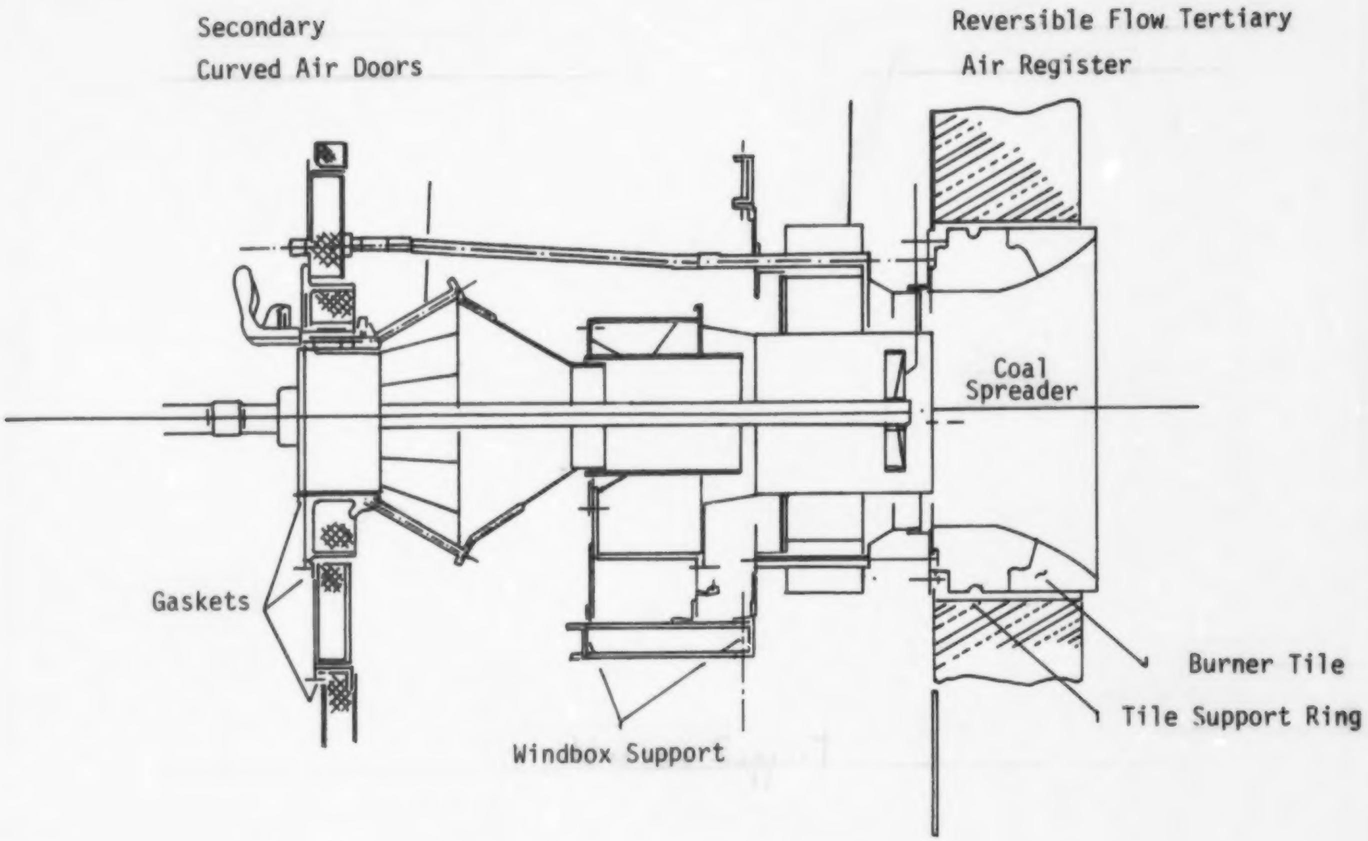
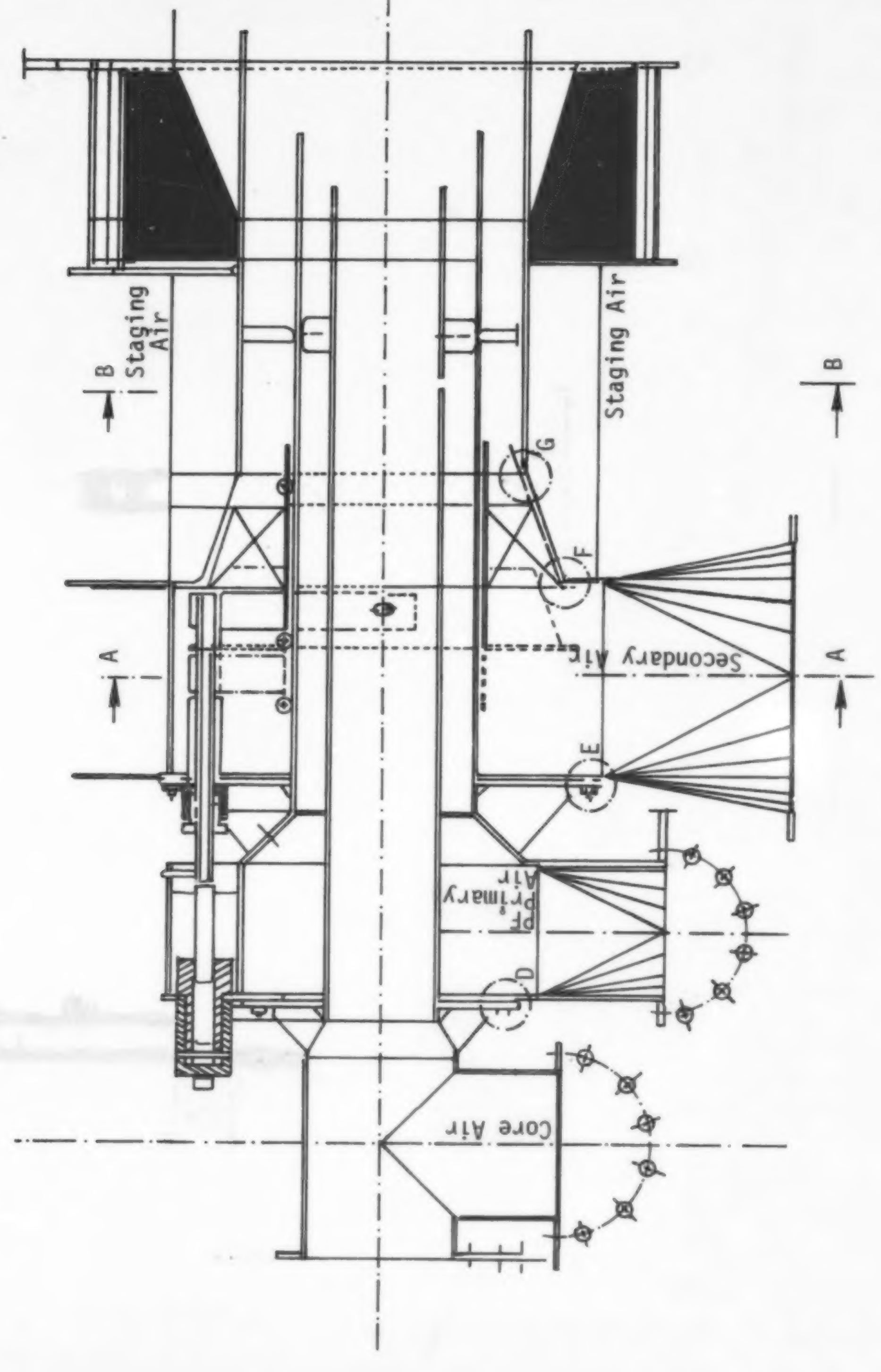

Secondary
Curved Air Doors
Reversible Flow Tertiary
Air Register
Coal
Spreader
Gaskets
Windbox Support
Burner Tile
Tile Support Ring

Figure 6-33. Peabody Dual Register Burner.



Staging Air
Staging Air
B
B
A
A
G
F
E
D
Secondary Air
PF Primary Air
Core Air

Figure 6-34. Steinmuller NO_x Staged Burner.

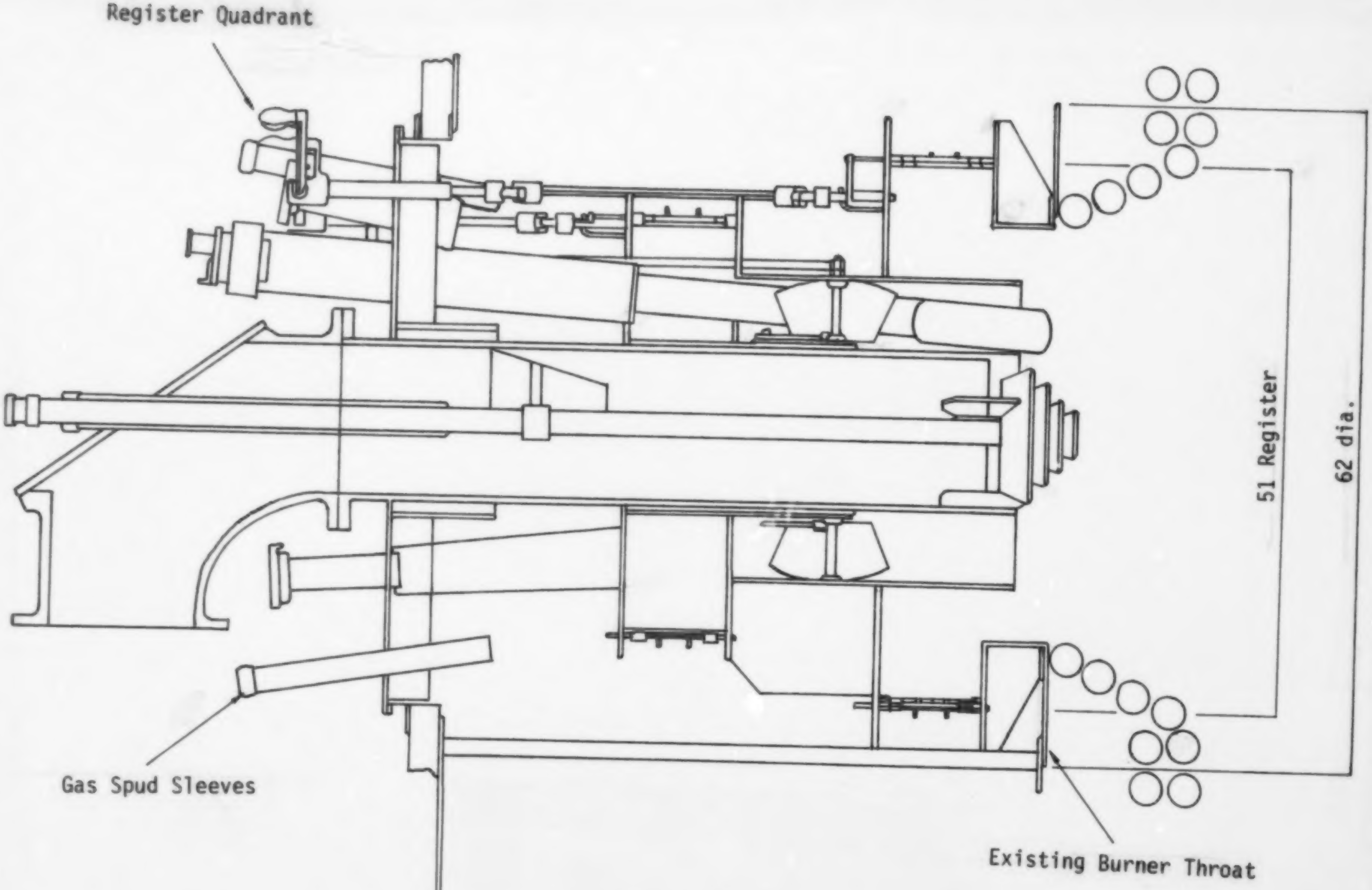

Register Quadrant
51 Register
62 dia.
Gas Spud Sleeves
Existing Burner Throat

Figure 6-35. B and W Dual Register Burner.

2. Fuel NO. Fuel-bound nitrogen is also oxidized during the combustion process giving both NO and N_2. The fraction of the fuel-bound nitrogen converted to NO is dependent upon the time/temperature history of the heterogeneous reactants.

This discussion will be limited to the influence of certain fuel and operational parameters on the conversion of fuel-bound nitrogen to NO, i.e., the formation of fuel NO_x.

The current hypothesis concerning fuel NO production in a pulverized coal flame results from a synthesis of information produced in several different experiments. Nitrogen in coal is almost exclusively associated with the organic content, and is evolved during coal particle heating in a similar manner to the hydrocarbon volatile matter. The amount evolved is dependent upon the particle temperature and the time at that temperature. Evidence exists suggesting that almost all the nitrogen can be driven from a coal particle if it attains a sufficiently high temperature. The volatile nitrogen may exist in two major forms. Some of the nitrogen will be evolved directly as light gases, such as ammonia or HCN. However, the bulk of the nitrogen driven from the coal will be in the form of heavy molecular weight hydrocarbon compounds whose molecular structure is similar to that of the coal. Further pyrolysis of these tars may also produce light gases as well as a nitrogen-containing solid. Thus, the fuel-bound nitrogen in coal can be subdivided into three groups:

- Char nitrogen. That nitrogen which remains in the parent coal particle after volatile evolution.
- Volatile nitrogen. That nitrogen evolved during particle heating with the volatile fractions. Volatile nitrogen compounds may undergo further pyrolysis producing nitrogen-containing solids similar to char nitrogen.
- Gaseous nitrogen. Those nitrogen compounds which are evolved from the coal directly or formed during secondary pyrolysis of coal volatiles. It is generally considered that the gaseous nitrogen compounds are rapidly converted to hydrogen cyanide.

The fractionation of the fuel-bound nitrogen between the three components described above will influence NO production under both excess air and staged combustion conditions. Therefore, those parameters which dictate the rate of evolution of volatile nitrogen compounds and the ultimate char nitrogen content will be important factors in the design of low NO_x combustion systems.

6.2.1 The Effect of Coal Type on Fuel NO_x Production

Figure 6-36 shows both the percentage of fuel nitrogen converted to NO as a function of the nitrogen content of the coal on a dry ash-free basis, and for a wide range of liquid fuels under well-mixed conditions at 5 percent oxygen. It can be seen that for the coals studied to date fuel nitrogen conversion is not strongly dependent upon total coal nitrogen content over the range 0.9 to 1.9 percent nitrogen. This can be contrasted with the conversion of fuel nitrogen in liquid fuels. For petroleum coal-derived and shale-derived liquid fuels, fuel nitrogen conversion decreases with increasing nitrogen content and the overall conversion is much higher in liquid than in solid fuels.

It can be argued that the difference between solid and liquid fuels is due to the partition of fuel nitrogen between the char and volatile fractions, and that char nitrogen conversion is much lower than volatile nitrogen conversion. This conclusion is borne out by several experiments but has yet to be proved conclusively. One other factor should be borne in mind when considering NO production in heterogeneous systems. This is the possibility of NO reduction either directly or catalyzed by solids. It is known that NO can be reduced by carbon; however, the presence of oxygen inhibits this reaction and under premixed conditions heterogeneous NO reduction might not be an important factor.

Future work will involve testing a much wider range of fuels and attempting to correlate fuel NO formation with fuel properties.

6.2.2 The Influence of Operating Parameters on Fuel NO Production

The results obtained to date with the distributing mixing burner indicate that its performance is dependent upon coal type. Under premixed conditions it appears that some property other than total fuel nitrogen influences fuel NO production. It is also known that several operating

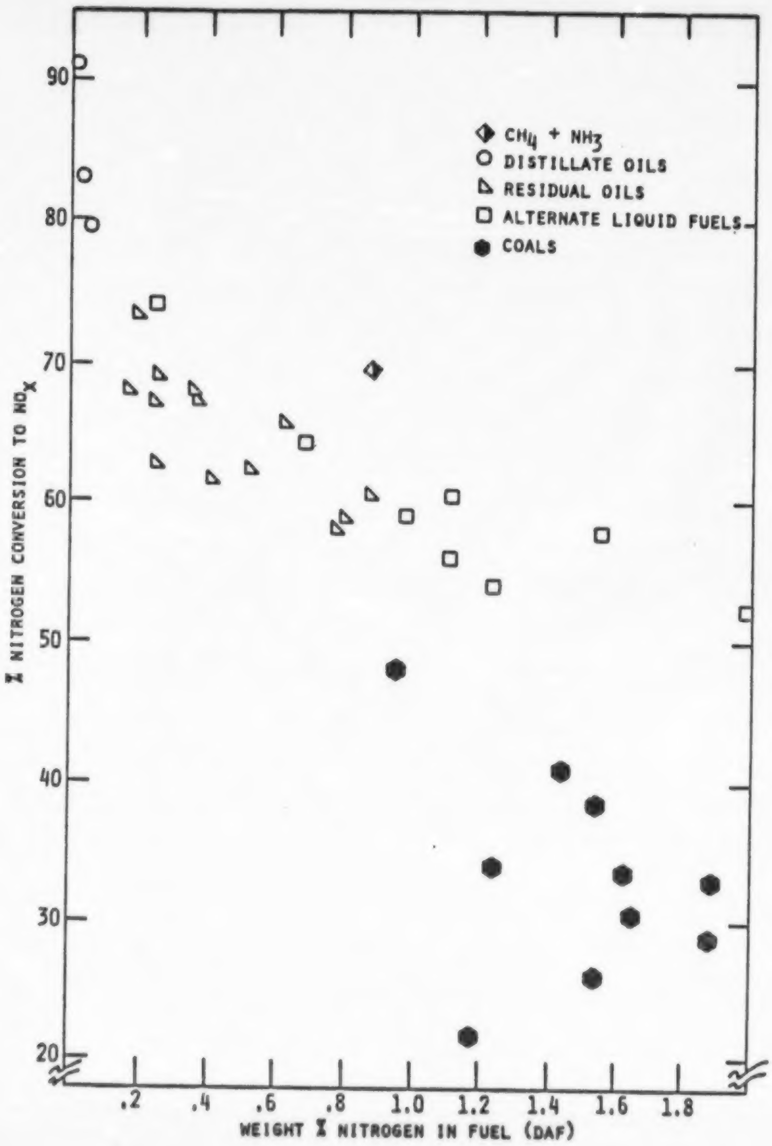


Figure 6-36. Effect of Fuel Properties - Overall Composite of Fuel Nitrogen Conversion.

parameters also affect fuel NO production. If both the heating rate and the final temperature of the coal particle have a strong influence on the partition of fuel nitrogen between the refractory and volatile fractions, then operational parameters which influence the thermal environment of the particle will affect fuel NO production. In the bench-scale experiments the thermal environment can be readily varied by changing the carbon dioxide/argon ratio which will influence flame temperature. The experimental results presented in Section 5.1 show a strong dependence of fuel NO production on flame zone temperature. The influence of thermal environment on fuel NO production was not observed with diffusion flames. If the efficiency of volatile fuel nitrogen conversion to NO is greater than that of char nitrogen, then under premixed conditions any increase in volatile nitrogen content would increase fuel NO production. Although the effect of CO_2 is primarily one of temperature variation, it should be remembered that fuel NO conversion may be different in artificial atmospheres from that obtained with air. However, there is strong evidence to suggest that the increase in fuel NO formation observed with increasing flame zone temperature is primarily due to an increase in volatile fuel nitrogen. The results with coal are contrary to those obtained with liquid fuels, suggesting another difference between these fuels in that the nitrogen contained in liquid fuels is evolved at relatively low temperatures compared to coal, and any increase in flame zone temperature will have a minimal effect on nitrogen evolution rate.

Fuel/air contacting will affect both the thermal and gaseous environment of the coal particles, and the latter may have the more significant effect upon fuel NO formation. Under premixed conditions oxygen is available to react with fuel nitrogen compounds as they evolve from the coal; thus, conditions are most conducive to fuel NO production. If the volatile compounds gradually diffuse from the surface of the particle, then the existence of premixed conditions may have a minimal effect since the fuel nitrogen compounds can react in a boundary layer which is deficient in oxygen. Alternatively, if the volatile fractions are ejected from the surface and mix with the surrounding gases some distance from the particle, then fuel nitrogen conversion to NO will be high. In the case of the axial diffusion flame even though the system is overall oxygen-rich the particles within the flame zone are separated from the oxidant by the heat release zone, thus providing those conditions which minimize fuel NO production, i.e., oxygen lean.

The results presented earlier showed that under excess air conditions small particles produced larger quantities of fuel NO. However, small particles were more amenable to NO reduction via staged combustion. The most simple explanation for these observations is associated with the time that the volatile fuel nitrogen compounds remain in the first fuel-rich zone. It can be argued that the volatile evolution from small particles is more rapid than that from large particles, thus giving a longer time for N_2 production in the fuel-rich zone. The effect of particle size with coal is consistent with observations that with liquid fuels NO_x emissions increase with increasing mean liquid droplet size under staged combustion conditions.

6.2.3 The Potential for Simultaneous NO_x/SO_x Emission Control

The incentive to produce a control scheme whereby two pollutants nitrogen and sulfur oxides can be controlled simultaneously by combustion modification is enormous. The major barrier to the increased use of direct coal combustion is the requirement to prevent SO_2 emissions. Sulfur can be removed prior to combustion by cleaning the coal physically and/or chemically (which does not normally remove sufficient sulfur) or by producing a clean fuel by liquefaction or gasification. In addition, it can be removed as the oxide after combustion by a stack gas cleanup process. Pretreatment plants are still in the development stage and stack gas scrubbers are expensive and increase power costs. Consequently, an inexpensive simple method of removing sulfur by adding a sorbent to the coal, burning the coal in a low NO_x mode and collecting the resulting spent oxide together with the fly ash is appealing. However, it is difficult not to be skeptical of its effectiveness and potential.

This report has:

- Described pilot-scale and field demonstrations concerning the use of dry sorbents.
- Presented results of an initial test series with an EPA low NO_x coal burner in which various sorbents were added to the coal before it was pulverized.

- Described bench-scale experiments which investigated the effect of sorbent dispersion, thermal and fuel/air contacting environment and combustion staging on sulfur capture.

Although the results of the burner and pilot scale tests appear to be encouraging they cannot be considered definitive since no solid sulfur measurements were made. Therefore these results should be treated with caution although they are similar to some results obtained in other systems.

Reviewing information on the process requirements suggests that the keys to the utilization of dry sorbents are:

- The provision of the optimum sorbent particle temperature history to ensure maximum calcite reactivity and residence time for absorption.
- Minimization of excessive particle temperatures to prevent both deadburning and regeneration.
- Dispersion of the sorbent so that the process is not mixing limited.

Summarizing all of the available information it appears possible that under certain circumstances, mainly those which restrict peak flame temperatures, it might well be possible to develop a combined NO_x/SO_x control scheme.

Before making plans to develop full-scale test programs a four step approach is recommended which will provide more definitive information as to the potential of this control strategy. These steps involve the development of measurement techniques, bench scale studies to define process requirements, pilot-scale studies to provide data at realistic scales and a systems study to evaluate the overall implications of the study.

Measurement of Sulfur Species

One major problem associated with the further development of a combined NO_x/SO_x control technique will be the establishment of a method to sample and analyze gaseous sulfur species from a combustion environment containing a reactive solid. This investigation must consider both oxidized and reduced sulfur specie.

Bench Scale Studies

These studies should be carried out under well-defined temperature and residence time conditions and allow for in-flame sampling in order to define under which conditions the sorbent is most reactive and in what form the sulfur is captured. Investigations should be carried out with a wide range of coal types. The primary objective of these studies is to define those conditions which will maximize sulfur capture and minimize fuel nitrogen conversion to NO_x.

Pilot Scale Studies

The objective of these studies is to assess the effect of burner design and scale on sulfur capture. These experiments should be carried out at a scale and in an environment similar to watertube boilers with several burner designs to ascertain which design comes closest to the limits of sulfur capture set by the bench scale studies.

Systems Study

Before any demonstration is considered, assuming the results of the other investigations are encouraging, a study should be initiated to:

- assess the capital and operating costs of the control technique;
- review the system requirements (sorbent type, availability, feeder requirements, pulverizer capacity, etc);
- overall environmental impact;
- solids disposal;
- effect on boiler operation (slagging, fouling, etc.);
- use in conjunction with baghouse or ESP.
- boiler configurations which give the required time temperature history for maximum capture.

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7.0 CONCLUSIONS AND FUTURE EFFORTS

The results of the bench-scale studies on the fate of fuel nitrogen during the combustion of solid fuels indicate that:

- With coal, fuel nitrogen content may not be the primary variable controlling the production of fuel NO_x.
- Fuel NO_x formation appears to be relatively insensitive to thermal environment for solid fuels burning in a diffusion flame, whereas there is a strong dependence of fuel NO production on flame temperature in premixed pulverized coal flames.
- Initial fuel/air contacting has a major impact upon fuel NO production under both staged and unstaged conditions.

A major factor affecting the fate of fuel-bound nitrogen, and therefore, fuel NO production during coal combustion appears to be the division of the nitrogen between the char and volatile fractions. Early evolution of volatile nitrogen compounds may maximize the benefits to be achieved from staged combustion.

The low NO_x burner has only been tested with three coals using two burner scales. These preliminary results obtained to date suggest that:

- Under optimum design conditions NO_x emissions are typically below 200 ppm (dry at 0 percent O_2) for the two burner scales (12.5 and 100 x 10^6 Btu/hr).
- NO_x emissions are dependent upon scale when a simple geometric scaling law is applied.
- The emission characteristics of the low NO_x burner appears to be mildly dependent upon coal characteristics.

The preliminary results involving the use of dry sorbents for SO_2 capture are encouraging. It can be speculated that the effectiveness of the low NO_x burner as a means of enhancing sulfur capture is associated with the following.

- Sorbent dispersion. Effective sorbent utilization requires that its concentration must be high and that it is evenly distributed in these regions where the sulfur specie are evolved from the coal. In the tests described above, the sorbent was mixed with the coal before the pulverizer, and therefore, was evenly dispersed in the form of small particles.
- Sorbent activity. The sorbent is in contact with high sulfur concentrations initially after calcination at the time it is most reactive. Also, the low NO_x burner probably provides the optimum time/temperature history for maximum sorbent activity and minimal deadburning.
- Peak flame temperatures occur under fuel-rich conditions. The sulfur and sorbent initially make contact under oxygen-deficient conditions and probably form a sulfide which is more stable at higher temperature than the sulfate. Consequently, decomposition of the "sulfur-containing sorbent" will be minimized.
- Reduced peak temperatures and low bulk gas temperatures. Low NO_x operation requires that peak temperatures are minimized, thus ensuring maximum residual sorbent activity to capture sulfur in the bulk gases after the heat release zone. The fact that the sorbent is evenly dispersed will also tend to maximize sulfur capture in this region.

These preliminary results suggest that the use of a flame zone sorbent plus baghouse might well be a viable SO_x control technology for low sulfur Western coals or an addition to physical or chemical cleaning for high sulfur coals.

During the second year of the Development of Criteria for Extension of Applicability of Low Emission, High Efficiency Coal Burners, major areas of endeavor will be the completion of the initial fuel screening tests, optimization of single burner parameters for multiple fuels, evaluation of fuel effects in multiple burner arrays, and comparison of the DMB with various commercial burners.

Since almost all of the initially selected fuels have been acquired, only the few remaining coals need be obtained. Most of the effort on fuels during the second year will be the acquisition of large quantities of the fuels which are specified from the fuels screening results for testing at large-scale. Another effort on fuels will be the acquisition of small amounts of the washed and treated fuels which have been selected for testing at small-scale for the second year.

A versatile burner designed according to the principles identified from Contract 68-02-1488 will be constructed for the SWS combustor. This burner will allow a rapid change of operational variables and design parameters, thereby providing for efficient optimization tests for the various fuels. Since a large range of properties of fuels will be investigated, versatility will be provided to allow rapid change of some major design parameters such as throat velocities independently of airflow and burner exit dimensions. The rapidity and versatility for changing operational variables will also be ideally suited for application of burner control systems. A similar but larger burner will be used later in the LWS combustor for optimization tests using the variable and parameter ranges that were narrowed by the cost-effective testing in the SWS.

Multiple burner tests will be underway during the second year. Initially, various fuels will be tested in different arrays for the single-wall firing mode. Sufficiently detailed in-furnace measurements will be accomplished to understand burner/burner and burner/chamber interactions to guide the steps to minimum emissions. Further tests will consider opposed-wall and corner-fired multiple burner modes for optimization studies.

Three commercially available burners will be tested in the LWS. These tests not only provide for evaluation of the combustor, but also a reference to extrapolate the experimental low NO_x burner performance in the LWS to field performance.

APPENDIX A

PROPERTIES OF COALS REFERENCED IN TEXT

Coal Number	1	2	3	4	5	6	7	8
Coal Description	Pittsburgh No. 8	Western Kentucky	Montana Powder River Region	Colorado Bear Mine	Texas Lignite	Pittsburgh Seam No. 8 Ireland	Montana Savage	Arkwright
Proximate Analysis								
Volatile	37.0	37.1	30.5	38.9	28.68	40.7	36.2	
Fixed Carbon	54.0	51.2	39.0	52.6	24.08			
Moisture	1.2	4.8	21.2	3.3	35.96	2.2	13.6	2.21
Ash	7.8	7.8	9.2	8.9	11.28		7.8	
Ultimate Analysis								
C	77.2	73.0	67.2	73.1	60.44	67.81	54.50	78.14
H	5.2	5.0	4.4	5.1	4.61	5.03	4.96	5.08
N	1.19	1.4	1.10	1.16	1.21	1.20	0.88	1.61
S	2.6	3.1	0.9	1.1	1.75	4.83	0.84	2.21
O	5.9	9.3	14.0	9.7	14.36	8.55	17.14	4.12
Ash	7.9	8.2	11.7	9.8	17.61	12.58	21.68	8.85
Heating Value, Btu/lb	13,700 (wet)	12,460	8,900	12,400	6,677		7,346	
ASTM Classification	HVA	HVB	SB	HVB	Lig.	HVA	Lig.	
Reference		4.1,3.2, 4.8,3.10, 4.17	4.1,3.2, 4.8,3.10, 4.17	4.1,3.2, 4.8,3.10, 4.16,3.17		4.1,3.6	4.1,3.6	4.2

APPENDIX A

PROPERTIES OF COALS REFERENCED IN TEXT

Coal Number	9	10	11	12	13	14	15	16
Coal Description	Wyodak	Illinois No. 6	Lignite	Lignite	Coal Used at Four Corners	Montana Rosebud	Peabody Deer Creek Mine	Montana Custer County (Old Weaver Mine)
Proximate Analysis								
Volatile					31			35.7
Fixed Carbon					34.5			43.1
Moisture	2.2	0.4	33.2	30.4	12.5	24.2	7.1	29.1
Ash					22.0	8.3	9.8	
Ultimate Analysis								
C	68.0	68.0	61.5	69.5	57.5			56.6
H	5.0	4.8	4.79	4.60	4.3			3.3
N	0.9	1.2	1.05	0.57	1.25	0.79	0.93	0.8
S	0.7	4.6	1.20	0.57	0.75	1.05	0.53	0.8
O	17.5	12.0	17.5	18.1	17	16.2	10.8	17.3
Ash	7.9	9.4	13.9	6.6	25	8.3		
Heating Value, Btu/lb			7,240	8,380	8,850	8,645	12,000 (wet)	6,600
ASTM Classification	SA	HVC	Lig.	Lig.	HVC	SC	HVB	SC
Reference	4.2	4.2	4.20	4.20	4.18	4.35	4.35	4.36

APPENDIX A

PROPERTIES OF COALS REFERENCED IN TEXT

Coal Number	17	18	19	20	21	22	23
Coal Description	Utah	COED Char			Lyons Seam Virginia PSOC 268	West Virginia No. 5 Block (Lower Kitt) PSOC 124	Pennsylvania Middle Kitt PSOC 330
Proximate Analysis							
Volatile	38.9	3.6	3.27	35	37.78	48.83	37.93
Fixed Carbon	47.3	73.8			62.13	41.78	55.96
Moisture	6.4	1.8					
Ash	7.4	20.8	6.3		5.09	9.38	6.22
Ultimate Analysis							
C	68.5	72.8	European Coal	European Coal	81.58	75.78	76.93
H	5.2	0.9			5.17	6.33	5.09
N	1.2	0.99			2.03	1.25	1.71
S	0.6	3.5			1.46	0.99	2.77
O	10.7	0.7			4.66	6.22	7.23
Ash	7.4	21.2			5.09	9.38	6.11
Heating Value, Btu/lb	12,340				14,696	14,474	13,730
ASTM Classification	HVB	— —			HVA	HVA	HVB
Reference	4.8,3.37	4.1,3.10	4.1,3.15	4.1,3.15	4.4,3.38	4.4,3.38	4.4,3.38

APPENDIX A

PROPERTIES OF COALS REFERENCED IN TEXT

Coal Number	24	25	26	27	28	29	30
Coal Description	Pittsburgh PSOC 170	Pennsylvania Pittsburgh PSOC 103	Hazard No. 7 BuMiK 40660	Ohio No. 2 PSOC 212	Ohio No. 5	Montana Lignite Savage	Pittsburgh Seam
Proximate Analysis							
Volatile		36.20			41.27		35.5
Fixed Carbon		57.13			47.63		56.2
Moisture							1.9
Ash		6.68					6.4
Ultimate Analysis							
C	75.4	76.91	71.8	77	69.57	72.6	76.9
H	4.9	5.26	4.9	4.9	5.00	3.6	5.2
N	1.36	1.25	1.37	1.6	1.57	0.99	1.6
S	2.16	0.82	2.17	0.9	4.34	1.1	1.1
O	8.6	9.01	8.7	12.6	9.22	23.9	8.7
Ash	8.5	6.68	13.2	3.05	10.20	6.8	6.4
Heating Value, Btu/lb		13,987			12,742		
ASTM Classification	HVA	HVA	HVA	HVC	HVB	Lig.	
Reference	4.4	4.4,3.38	4.4	4.4	4.4,3.38	4.4	4.13

APPENDIX A

PROPERTIES OF COALS REFERENCED IN TEXT

Coal Number	31	32	33	34	35	36
Coal Description	Utah	Ohio	Wyoming	COED Char	ARMCO Coke	ARMCO Coal
Proximate Analysis						
Volatile	45.2	38.6		7.77	0.89	25.36
Fixed Carbon	43.3	49.4		77.69	88.12	65.46
Moisture				3.19	0.41	3.32
Ash				11.35	10.58	5.86
Ultimate Analysis						
C	70.5	68.9	67.4	75.81	85.49	80.93
H	5.6	4.8	5.5	2.06	0.29	4.75
N	1.5	1.07	0.9	1.80	0.55	1.06
S	0.6	2.77	1.2	2.78	2.05	3.332
O	12.2	10.4	13.4	3.01	2.05	3.32
Ash	9.0	12.1	11.3			
Heating Value, Btu/lb		12,230 (dry)	11,863			
ASTM Classification			HVB			
Reference	4.14	4.16	4.22	4.23	4.23	4.23

APPENDIX B

COALS SELECTED FROM PENN STATE-ERDA SAMPLE BANK

NO.	PSOC	ASTM Rank	% N_2	% S	O_2/N_2
A	92	Lig.	0.52	0.92	40.6
B	245	Lig.	0.11	1.32	166
C	246	Lig.	1.4	0.65	14
D	138	Sub C	0.33	0.68	53.1
E	139	Sub C	1.1	0.76	15.3
F	65	Sub B	0.74	0.29	15.7
G	231	Sub B	1.63	0.39	9.6
H	97	Sub A	0.52	1.23	30.4
I	248	Sub A	1.68	0.64	10
J	59	HVC	1.84	0.5	8.1
K	154	HVC	0.44	1.19	30.33
L	316	HVC	2.19	0.52	5.6
M	105	HVB	0.39	2.21	28.6
N	272	HVB	2.2	4.15	3.3
O	121	HVA	1.75	1.22	3.75
P	125	HVA	0.75	1.87	5.6
Q	163	HVA	0.16	6.07	32.7
R	267	HVA	2.38	1.96	2
S	136	NV	1.7	0.58	2.8
T	130	MV	1.05	0.52	3.05
U	320	MV	1.86	1.16	1.4
V	113	LV	1.03	3.10	2
W	143	LV	1.36	0.65	2.74
X	85	An	0.55	1.05	5.2
Y	82	An	1.05	0.52	2.8